Marine Propulsion
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Lecture - 27
Propeller Strength (Part - II)

Welcome to lecture 27 of the course Marine Propulsion. Today, we will continue with Propeller Strength.

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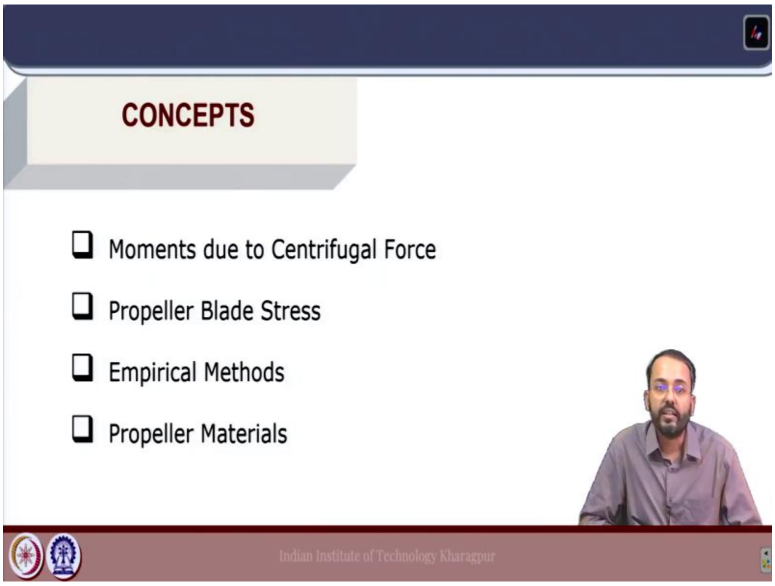

The aspects of propeller blade strength to be covered in this lecture include the moments due to centrifugal force on the propeller blade. The propeller blade stresses that arise from the combination of different forces some empirical methods which are used to calculate stresses for the propeller blade. And finally, we will discuss on the materials which are used for manufacturing propeller blades.

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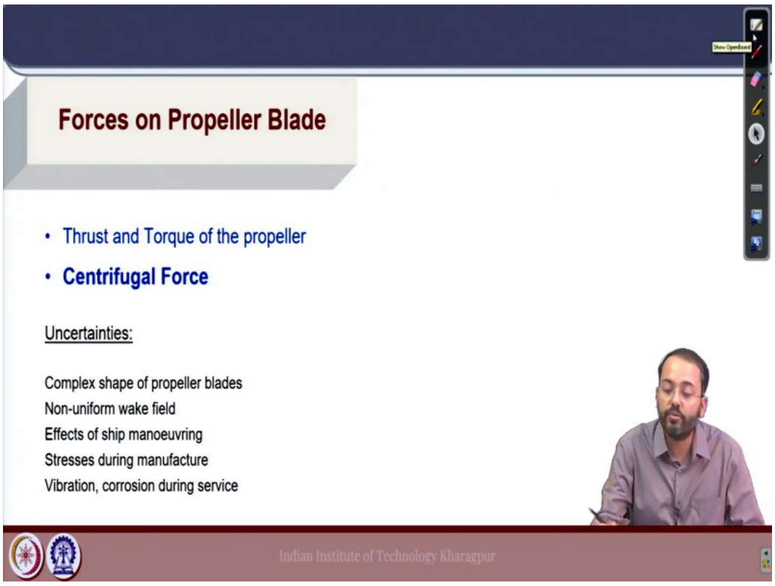

Now, we have already discussed that based on the simple calculation for the cantilever beam theory for propellers, the forces which are considered to calculate the stress on the propeller blade are thrust and torque of the propeller and centrifugal force. Now, the moments due to thrust and torque have been discussed in the previous lecture. And, today we will discuss the impact of centrifugal force on the moments generated on the propeller blade.

And, we have also discussed about certain uncertainties like the complex shape of propeller blades, non-uniform wake field, different operation conditions like manoeuvring, stresses during manufacture and service conditions like vibration or corrosion which impact the forces and stresses on the propeller blade. So, the beam theory that we are using for calculation of the moments and finally, stress on the propeller blade assumes that the main forces are the thrust and torque on the propeller and the centrifugal force.

And the other conditions like uniform flow assumption and the variation of thrust and torque only along the radius are the basic assumptions. And we do not consider complex flow effects and effect of non-uniform wake field, these are not included in this simple calculation. So, we will go ahead to look into the moments generated due to the centrifugal force on the propeller blade.

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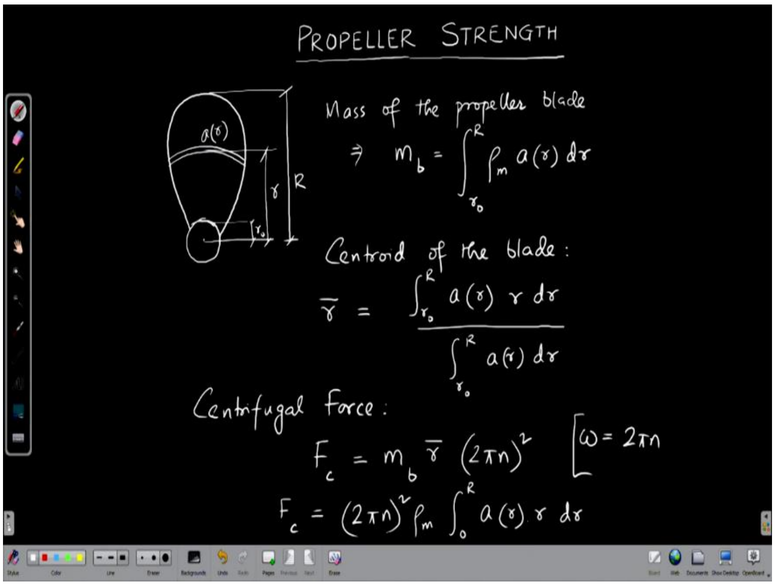

First, let us try to calculate the mass for a propeller blade. So, if we take a strip at a radial location r, where the area of that strip is a as a function of r. Then, mass of the propeller blade is m blade equals integration on the limits where the propeller blade exists; that means, from the root of the blade to the tip ρ times a as a function of r integrated over the entire blade; where, ρ_m is the density of the propeller blade material; and m_b is the mass of each blade of the propeller between the root and the tip.

$$m_b = \int_{r_0}^{R} \rho_m \, a(r) dr$$

Now, the centroid of the blade can be given as the distance from the axis the radial distance using this expression the moment of this area divided this integration.

$$\bar{r} = \frac{\int_{r_0}^{R} a(r) \, r \, dr}{\int_{r_0}^{R} a(r) dr}$$

Now, the centrifugal force on the propeller blade is due to the rotation of the propeller blade. And it will depend on the rpm that the propeller blade is having for a specific operation condition. So, centrifugal force F_c let us say is given by the mass (m_b) × the distance of the centroid ($\bar{r}$) × ω^2 which is(2 π n), where ω = 2 π n. $m_b \times \bar{r} \times \omega^2$ the expression for centrifugal force.

So, based on the calculations for mass and the centroid, F_c can be written as $F_c = (2\,\pi\,n)^2 \times \rho_m$ × integration of the area multiplied by r.

$$F_c = (2\,\pi\,n)^2 \times \rho_M \int_0^R a(r)\, r\, dr$$

This is the expression for the centrifugal force on the propeller blade. Now, similar to the thrust and torque calculation, we will calculate the moments on the propeller blade at the root section due to this centrifugal force.

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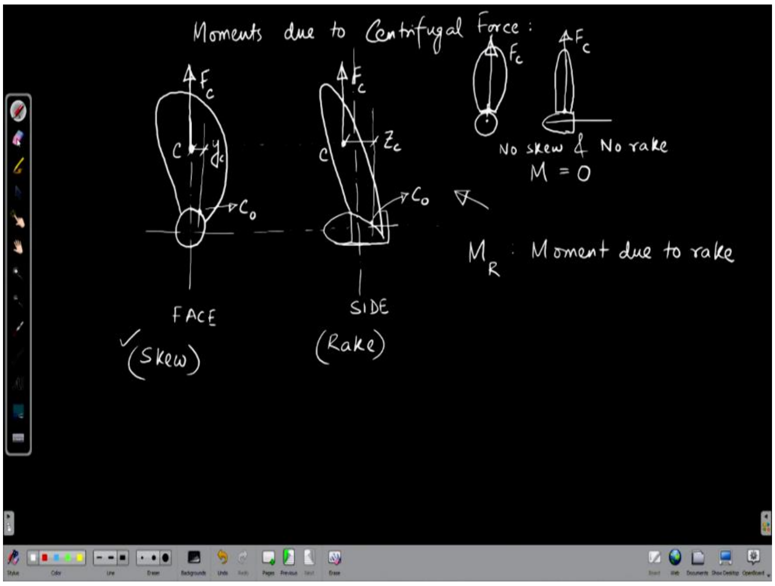

So, we need to understand the moments due to centrifugal force. Let us again look into two different views of the propeller blade; the view from the face and the view from the side. Now, let us say this is the location of the centroid of the propeller blade which mapped in this particular view as the location here, which is C. And, we have the centrifugal force F_c away from the propeller center, outside. And, we want to calculate the moments about the section at the root of the propeller blade as has been done for the thrust and torque.

We have to take the centroid of the root section. Let us say this particular point is the centroid C_0 for the root section and here it is this C_0. So, if we draw a vertical line through this centroid at the root, we can draw an axis here. This particular distance will be the arm for the moment about the root section in the side view. And, this length is the arm in the face view let this be designated as y_c and this as Z_c.

As we see for the two different views of the propeller blade the blade is generally skewed back and also may have an aft rake. So, this particular view face gives the skew of the propeller blade and the side view gives the rake of the propeller blade. These terms have been discussed in the propeller geometric class. Now, due to this skew and rake the moments will arise from the centrifugal force.

If we have a propeller where there is no skew, then the centrifugal force would have acted radially outwards and the location of the centroid of this root section would also be in line with that force. So, there would have been no moment. So, these moments due to centrifugal force arise due to skew of the propeller blade in the face view. And from the side view the moments due to the centrifugal force arise due to the rake of the propeller blade.

Similarly, if the propeller blade did not have any rake, then the centrifugal force would have acted along this line. And there would have been no momentum with respect to the centroid of the section at the base. So, if there is no skew and no rake, these moments would be 0, ok. So, the moments due to centrifugal forces will be named based on the angles for which the moment arms are created. The first one here is the moment due to rake. We come back again to the original diagram here.

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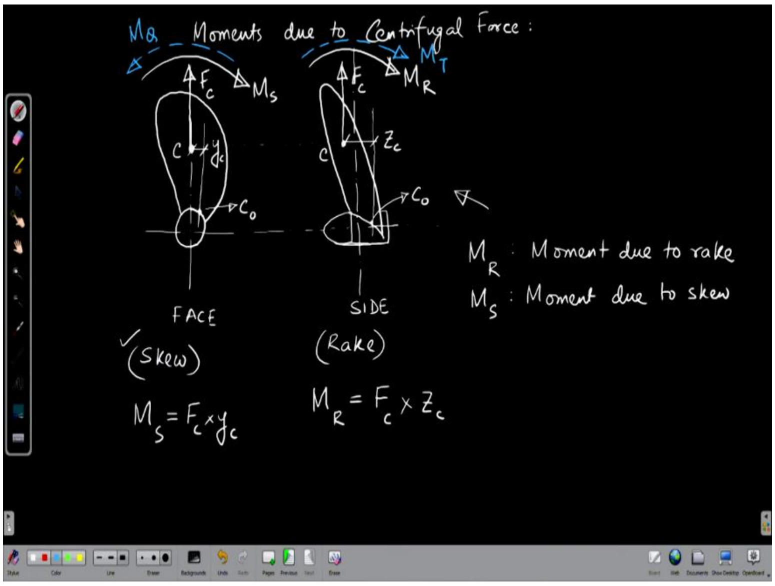

Let me remove this so that there is no confusion; and M_S is the moment due to skew. Now, the moments will be given by the multiplication of the force and the arm which is the distance between the point of action of the centrifugal force and the centroid at the root of the propeller blade about which we are calculating the moments. So, M_R, the moment due to rake is $F_c \times Z_c$ where Z_c is the moment term here and similarly for this skew $M_S = F_c \times y_c$.

Now, if we look at the direction of these moments this is the moment due to rake and similarly this is the moment due to skew. If we remember the moments that we had drawn previously the moments due to thrust and torque, we will see that the moment due to thrust was also drawn in this direction M_T; and the moment due to torque was drawn in the reverse direction as compared to the moment due to skew.

So, the effect of rake will add up as a moment addition to the moment due to thrust. And the effect of skew will be subtracted such that the moment due to skew will lower the moment which was originally due to torque in the direction which is normal to the direction of the propeller axis.

Now, for moderately skewed propellers, the value of M_S is not very high. Hence, the moment due to skew may be neglected for practical calculations, because if we neglect the moment due to skew the stress calculation that we do is on the more conservative side as this moment due to skew is subtracted from the moment caused by torque.

But, for heavily skewed propellers where the blade skew angles are very high, the moment due to skew may be quite high considering the different conditions of operation for the propeller blade. And in those cases these moments due to skew also needs to be considered.

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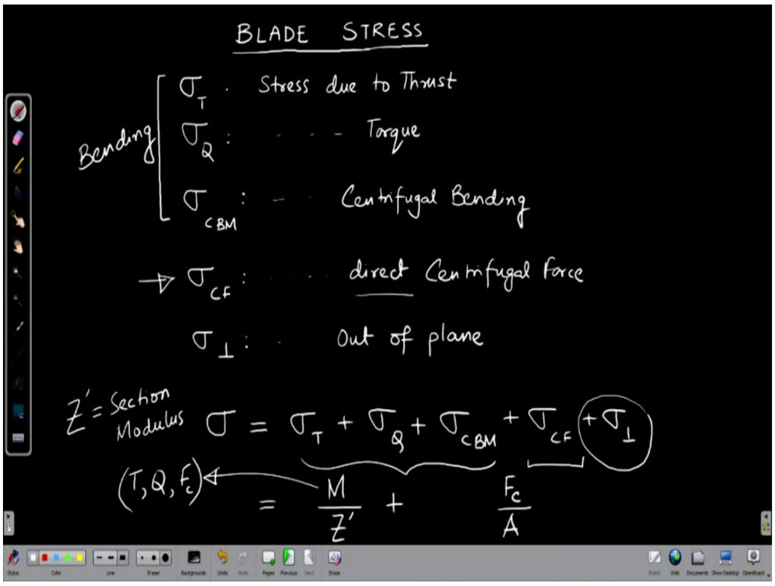

Now, let us look into the stress components on the propeller blade. The stresses on different sections of the propeller blade will depend on the radial location of the specific section and the sectional properties. Now, we have computed the moments due to the thrust and torque and centrifugal force on the root section. The stresses can also be computed on the root section based on these calculations.

So, the stress components will be stress due to thrust σ_T, σ_Q stress due to torque, σ_{CBM} stress due to centrifugal bending. We will come to these one by one. σ_{CF} stress due to direct centrifugal force and $\sigma_{\perp}$ some out of plane stresses denoted by this symbol, stresses out of plane ok. This is one way of representation of the blade stresses. There are many ways in which these can be computed or represented.

Now, we have computed the moments due to thrust and torque and also the moment due to centrifugal bending; that means, the bending moments due to thrust, torque and centrifugal forces have been computed. Now, the centrifugal force acts radially outward and because of that it will cause both a bending stress as well as a direct stress ok. So, the first three components these arise from bending.

And, the fourth one here is the direct stress due to the centrifugal force. So, if we write the total stress which is a summation of all these stresses $\sigma_T + \sigma_Q + \sigma_{CBM} + \sigma_{CF} + \sigma_{\perp}$ out of plane stress. So, the combination of these three $(\sigma_T + \sigma_Q + \sigma_{CBM}) = M/Z'$ can be written in this form for a particular blade section where M is the total moment due to the action of thrust, torque and centrifugal force.

So, M has combination of thrust, torque and centrifugal force; the total bending moment from these. So, this is the bending stress part; and Z’ is the section modulus for the blade section where we are computing the stresses. Z’ is used here because the term Z is used as the blade number. So, to make a difference from that, I have put Z’ here for the section modulus at the particular section where we are computing the stresses.

And the effect of direct stress is the centrifugal force divided by the area of the section force by area which is the direct stress for that section. Now, the last part this out of plane forces can be ignored for practical calculations. So, this is a way of using the forces on the propeller blades to calculate the bending moments and finally, the stress over any section of the propeller blades. Let us come back to our presentation where we will discuss some empirical methods for stress calculation on the propeller blade.

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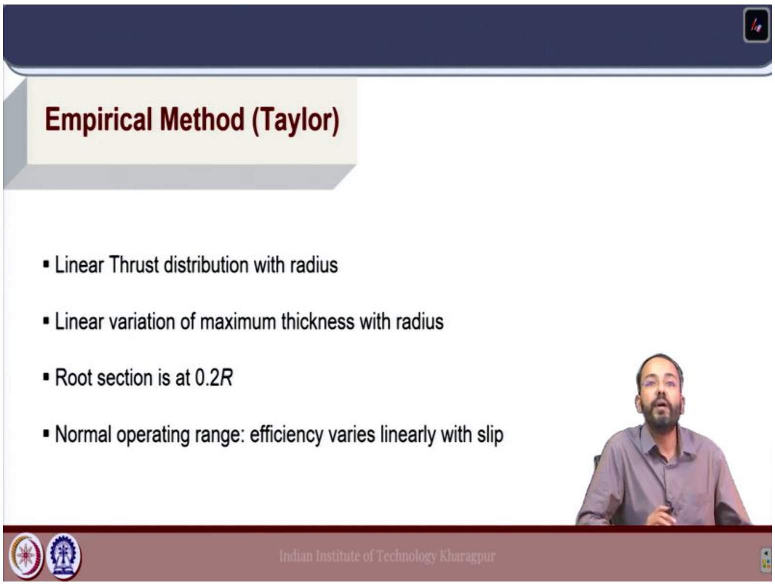

The first method that will be discussed is the method by Taylor where based on these certain assumptions the stresses at the root section for a propeller blade are calculated. So, the assumptions are linear thrust distribution with radius, linear variation of maximum thickness for the different blade sections with radius, the root section at 0.2R which is a steady standard approximation for conventional propellers, and the normal operating range is considered where the efficiency is assumed to vary linearly with the slip.

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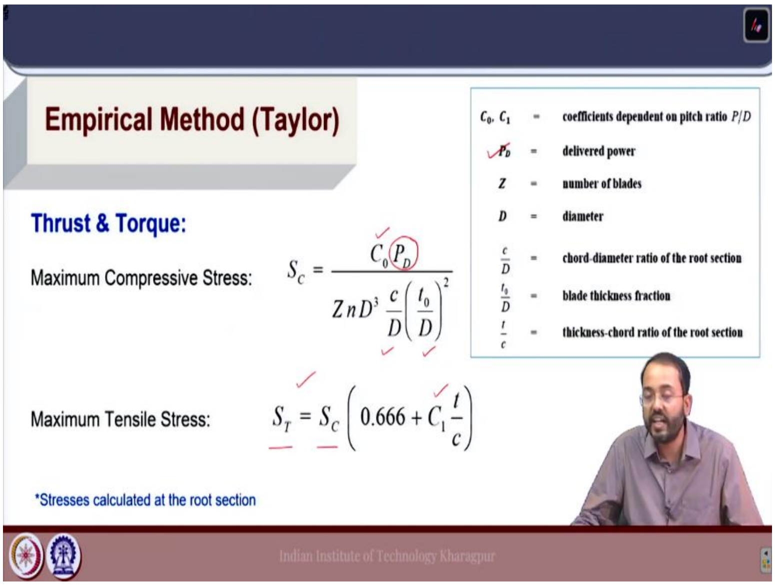

So, based on these assumptions Taylor had devised some formula which can be used for calculation of the maximum compressive and tensile stresses on the propeller blades due to thrust and torque and centrifugal force. So, if we look at the maximum compressive stress due to both thrust and torque calculated at the root section we will see that the maximum stress is a function of certain parameters of the propeller blade some geometrical parameters and some operational parameters.

Now, these parameters are a combination of both operational parameters like the delivered power here. And certain geometric parameters like the number of blades, diameter, chord diameter ratio, thickness fraction and thickness chord ratio which impacts the stress calculation for the propeller blade. And this method calculates both the compressive and tensile stress as a combination of thrust and torque. And these equations have certain coefficients C_0, C_1 which depend on the pitch ratio of the propeller blade.

If we look into the expressions carefully the stresses are proportional to the delivered power P_D. Here the tensile stress is also given by the compressive stress itself multiplied by this particular expression; that means, the P_D term is also included here; that means, higher the delivered power for the propeller the higher will be the stresses on the propeller blade right because for the same propeller the loading will increase.

Similarly, the terms c/D and t_0/D are in the denominator; that means, the higher the chord diameter ratio or the higher blade thickness fraction, the lower will be the stress on the propeller blade under the same loading conditions which is obvious because if the blade thickness fraction is high then the stress at that particular section of the propeller blade will be low. So, these empirical expressions can be used to evaluate the stresses on the propeller blade for a certain range of operation conditions and in a range of configurations for which these methods are applicable.

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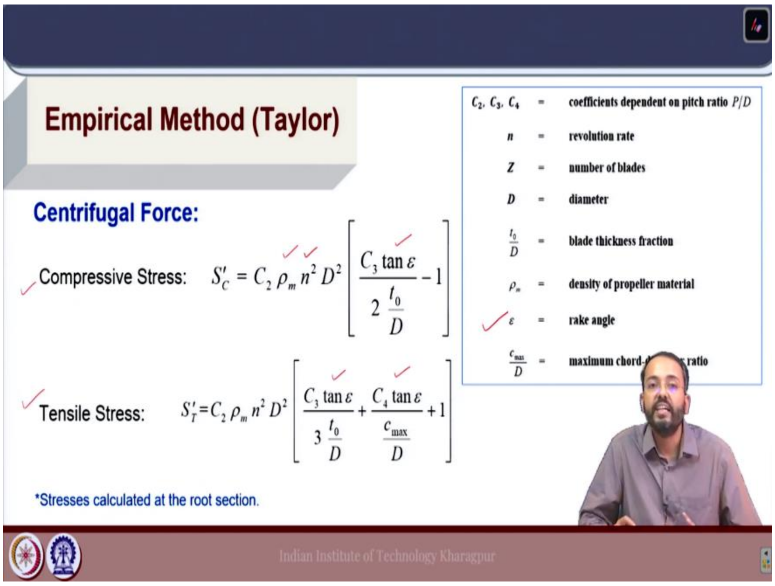

Similarly, we have expressions for the centrifugal force; the compressive stress due to the centrifugal force will now depend on additional terms like RPM and the density of the propeller material. As we have seen earlier in the centrifugal force calculation and the moments due to the centrifugal force we have these terms. And additionally the coefficients C_2, C_3 and C_4 are used here for the compressive and tensile stress due to the centrifugal force at the root section.

So, for the centrifugal force we will need the rake angle of the propeller blade. And here also we see that the skew is neglected for moderately skewed propeller blades this empirical method can be applied where only the stresses due to rake are computed. So, this is appearing here in these expressions which are functions of the rake angle both the compressive and tensile stress. And again we have the geometric parameters t_0/D and c_{max}/D in the stress equations.

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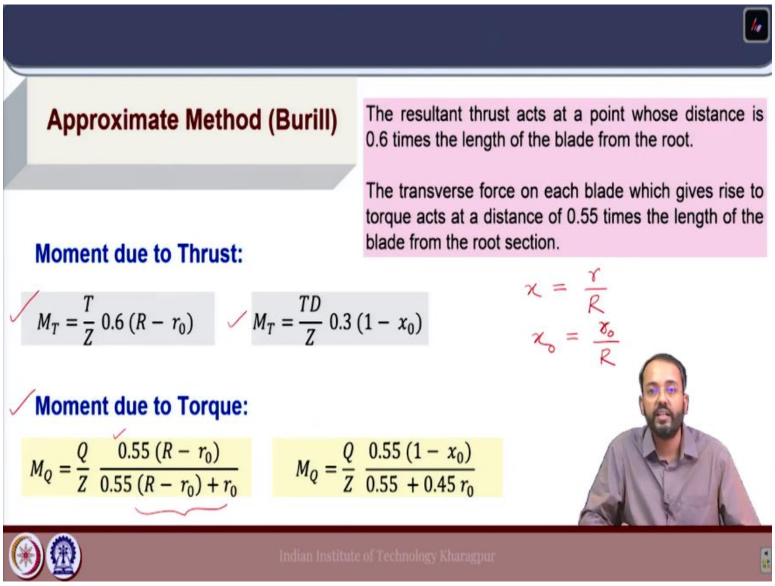

Next, we will look into another approximate method for blade stress calculation. The assumptions are that the resultant thrust is acting at a point whose distance is 0.6 times the length of the blade from the root. And similarly the transverse force which causes the torque is acting at a distance of 0.55 times the length of the blade from the root section.

So, here the points of action of thrust and torque are taken slightly different based on experience for different types of propeller blades. And accordingly the moments due to thrust and torque are simply calculated based on a similar fashion that has been used for the beam theory for propellers that we have used to compute the moments due to thrust and torque.

So, for the moment due to thrust the equation is T/Z multiplied by 0.6 which represents the location of the thrust force on the propeller blade and its distance from the root × (R - r_0) which is the location of the root of the propeller blade. And again if we non dimensionalize this with respect to the radius such that x is r/R. And similarly x_0 will be r_0/R.

We get this equation for the moment due to thrust. And similarly for the moment due to torque because the distance assumed is 0.55 times the length of the blade from the root section. Here, instead of 0.6, we will have the multiplied as 0.55. And additionally we have a length term in the denominator because instead of thrust the torque itself is used as a moment in this particular equation.

So, this Burrill's method also can give the moments on the propeller blade due to thrust and torque. If the value of thrust and torque and diameter and the number of blades for the propeller is known, this can be used as a simple representation of the moments acting due to thrust and torque on the propeller blade.

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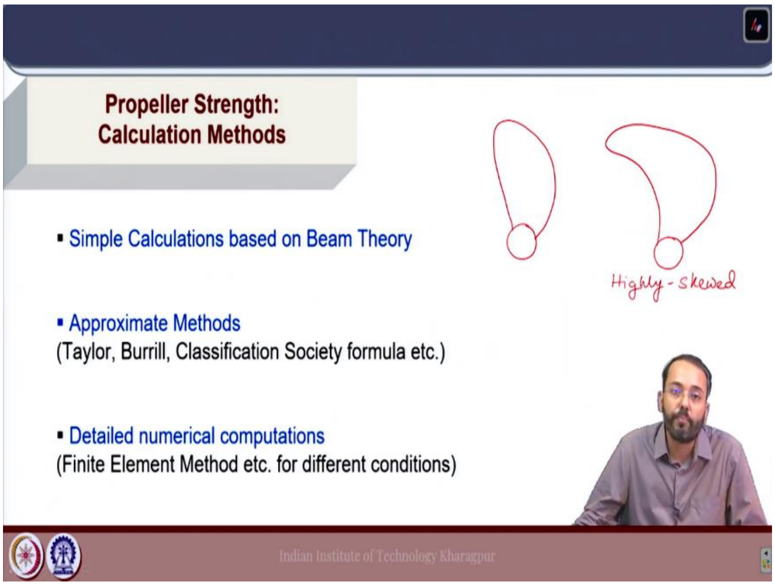

So, if we try to sum up the different methods which can be used for strength calculation of propeller blades. First, we have the simple calculations based on the cantilever beam theory where the moments due to thrust torque and centrifugal force can be calculated on the propeller blade section and from the moments the stresses can be calculated as both bending stress and direct stress.

Next, we have the approximate methods by Taylor and Burrill that we have seen which can be used to calculate the moments and stresses on the propeller blade sections. There are certain formula developed by classification societies which are used for strength calculation for propeller blade and also for designing the blade sections based on certain geometrical and operational characteristics of the marine propellers which are often used to define the blade parameters with respect to the strength requirements.

And finally, more detailed numerical computations can be used for example, using finite element method for different operation conditions where detailed calculation of propeller blade stresses can be obtained given the exact hydrodynamic loads for a particular operation condition. So, let us take a simple example here just to show the relevance of these difference methods let us take a propeller blade with a very moderate skew and another propeller blade where the blade has a high level of skew.

Now, for these special designs like highly skewed propeller blades and also special operation conditions, the blade stresses cannot be simply computed using simple calculations or approximate methods which are valid only within a certain range of designs and applications.

In those specific cases, it will be useful to perform numerical calculations as discussed using finite element approach or suitable methods to estimate the stresses for actual conditions or the specific designs so that for the particular material used for the propeller blade the stresses are within the allowable limits. Next, we will move on to the materials which are used for propeller blades.

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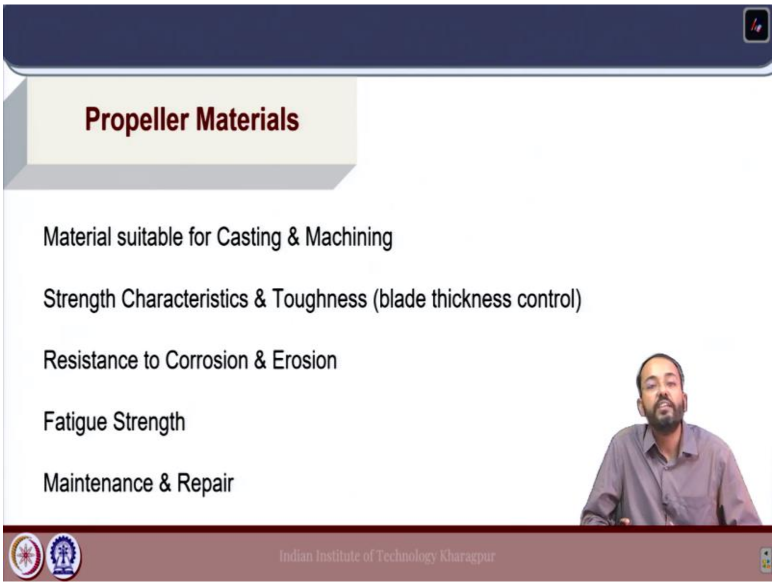

So, what are the basic criteria that needs to be satisfied when a material is chosen for a propeller blade? The material should be suitable for casting and machining which is the basis of manufacturing for the propeller blade. The strength characteristics and toughness is very important because that will control the thickness of the propeller blade sections.

The higher the strength characteristics the lower will be the requirement for the blade thickness for a specific loading condition. Next, resistance to corrosion which is very critical in the sea environment and also erosion due to cavitation occurrence for specific conditions. Fatigue strength over the entire design life cycle of the ship and ease of maintenance and repair for the propeller blades.

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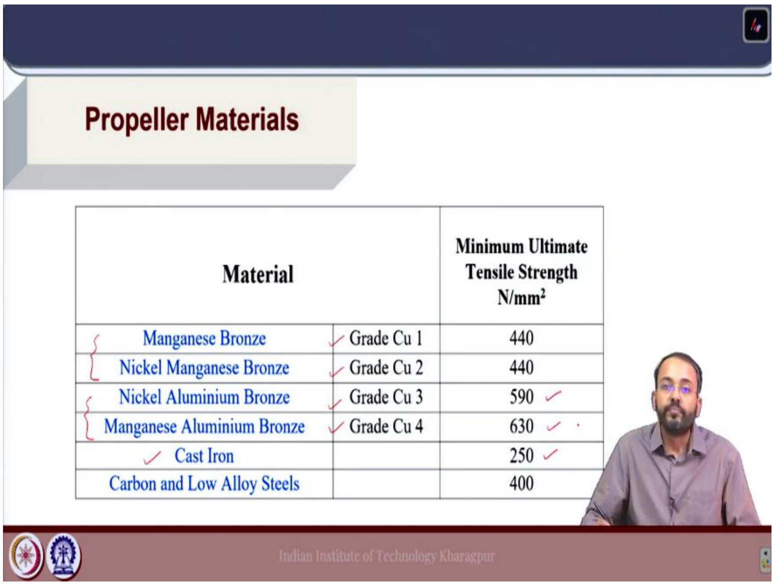

Material		Minimum Ultimate Tensile Strength N/mm²
Manganese Bronze	Grade Cu 1	440
Nickel Manganese Bronze	Grade Cu 2	440
Nickel Aluminium Bronze	Grade Cu 3	590
Manganese Aluminium Bronze	Grade Cu 4	630
Cast Iron		250
Carbon and Low Alloy Steels		400

Next, we will look into the different materials which are used for standard manufacturing of propeller blades. One of the oldest applications for marine propellers is cast iron which was used for old ships which has a value of the ultimate tensile stress 250 N/mm^2. And in recent times we use different alloys of copper which are of very high strength with certain other metals like manganese, nickel and aluminium.

So, these alloys are named with different grades here. Grade Cu 1, 2, 3 and 4 based on their characteristics as well as the ultimate tensile strength. Here, we see that the tensile strength of these alloys are very much higher as compared to cast iron and even compared to carbon steel. So, the first two alloys they have a similar strength which are manganese bronze and nickel manganese bronze. And Cu 3 and 4, nickel aluminium bronze and manganese aluminium bronze have very high tensile strength given here.

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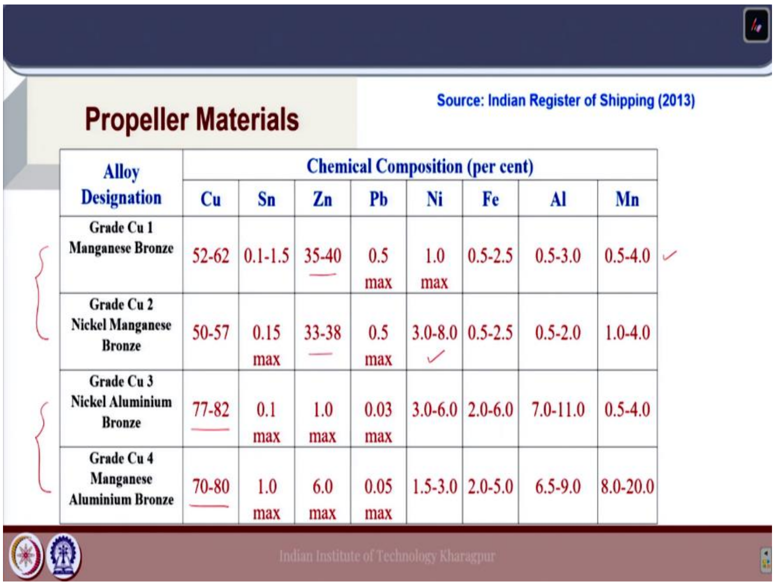

Alloy Designation	Chemical Composition (per cent)							
	Cu	Sn	Zn	Pb	Ni	Fe	Al	Mn
Grade Cu 1 Manganese Bronze	52-62	0.1-1.5	35-40	0.5 max	1.0 max	0.5-2.5	0.5-3.0	0.5-4.0
Grade Cu 2 Nickel Manganese Bronze	50-57	0.15 max	33-38	0.5 max	3.0-8.0	0.5-2.5	0.5-2.0	1.0-4.0
Grade Cu 3 Nickel Aluminium Bronze	77-82	0.1 max	1.0 max	0.03 max	3.0-6.0	2.0-6.0	7.0-11.0	0.5-4.0
Grade Cu 4 Manganese Aluminium Bronze	70-80	1.0 max	6.0 max	0.05 max	1.5-3.0	2.0-5.0	6.5-9.0	8.0-20.0

Now, we will look into the composition of these alloys based on the different metals which are used. So, the first two that we have just studied Cu 1 and Cu 2 have a similar copper composition along with a comparatively higher zinc composition as compared to Cu 3 and 4. The first one is manganese bronze. So, there is a good proportion of manganese; and the next one is having a comparatively higher proportion of nickel.

For the third and fourth alloys, Cu 3 and 4 we have a much higher composition of copper in the alloy in the range of 70 to 80 percent or more. And we have nickel aluminium and manganese aluminium as the two variants. So, these alloys are effectively used for their high value of tensile strength which is essential for the stresses developed on the propeller blade during different operation conditions.

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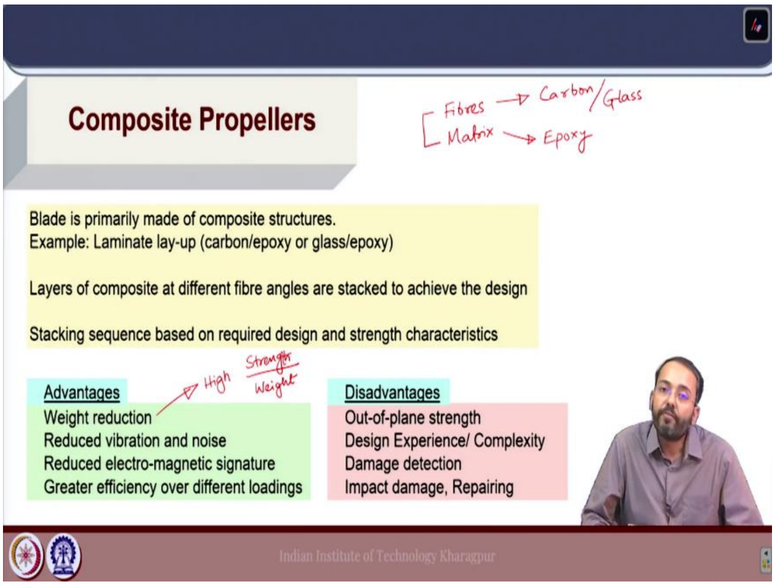

Another aspect which should be discussed in this part of the marine propulsion course is the concept of composite propellers. Composites are now widely used in both the aerospace and the marine industry because of their certain advantages with respect to structural construction. For marine propellers, composite materials find their application in a certain range of vessel lengths and their tonnages depending on the size of the propeller in those particular vessels and certain advantages have been reported.

So, what is the difference for these composite materials as compared to the metals? Here, we have the blade which is basically composite structure; that means, it is a composition of different structural elements. For example, it is mainly of laminate lay up where we have carbon epoxy or glass epoxy materials used as a composite material; that means, it has fibres and matrix.

So, these fibres can be carbon or glass which reinforce the matrix which is the epoxy material. It is somewhat similar in concept to the reinforced cement concrete which is used for civil construction, where here we have the fibres; that means, glass and carbon fibres which form the reinforcements and the matrix is the epoxy material.

The structure is typically of laminate lay up; that means, layers of composites for different fibre angles are stacked to achieve the particular design of the propeller. Based on the strength requirement we have different orientations of these fibres because it is the carbon and glass fibres which take the tensile strength. So, depending on the different sections of the propeller blade different angles of these fibers are used and stacking sequences are used to form the composite propeller blade.

And the strength characteristics of the final blade depends on the laminate layer and the layers that are used with different stacking sequences. If we simply look at the advantages which have been reported by use of composite material. One of the basic advantages is the weight reduction because these composites are lightweight and the strength of carbon and glass fibres in terms of tensile strength is quite high.

So, weight reduction which gives rise to high strength by weight ratio which is a very positive quality for any engineering structure. Next, certain cases of reduced vibration and noise have been reported with composite structures reduced electromagnetic signature which is critical for certain class of vessels typically naval vessels, because composites will have much reduced signature in terms of electromagnetic nature as compared to metal blades and greater efficiency over different loadings.

These composite materials depending on the hydrodynamic load can bend and that changes the shape of the propeller blade section. And certain advanced analysis have been done for composite propeller blades, where it has been found that these bending under different loads can be properly utilized to obtain different blade geometries over a different range of operation conditions which can give, in general a better range of the efficiency for different propeller loadings as compared to a design where the blade geometry is fixed.

Now, if we look at the main disadvantages of composite materials there are critical issues with out of plane strength, because these fibres which have very high tensile strength along the length of the fibre and they have to be properly oriented so that the different propeller blade sections can take the stresses for which it is designed. And if there are out of plane stresses then the strength may be an important factor if the fibres are not properly oriented.

Regarding design experience, designers have many decades of experience for designing metal propellers. Based on certain established procedures, we have been designing metal propellers for different design conditions based on the higher dynamics, strength and cavitation characteristics. But, for composites the application is very new and the complexity is quite high in terms of the orientation of the fibres and the stacking sequence for different blade section of the propeller blade. So, that is very critical.

Damage detection is very difficult for composites in addition there are issues with impact damage and repairing which is very difficult for composite materials. So, normally composite propellers find their application in certain propeller designs of restricted diameters where they have been effectively applied for their high strength weight ratio. And certain advantages have been obtained in terms of performance. This will be all for the discussions on propeller blade strength.

Thank you.