Mechanical Behavior of Materials -I
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Lecture - 45
Mechanical Behaviour of Composites

Welcome back students. So, we are now close to the end of the first part of this course mechanical behaviour of materials. And to end this we will introduce you to some fundamental mechanical properties of composites. And we will continue our understanding about the composites in the next part which is part 2 of mechanical behaviour of materials. So, let us begin.

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So, what is a composite? Basically, composite is a material which is consisting of two or more distinct phases and which are suitably arranged or distributed. And in this as you would see one phase becomes the matrix phase which is larger infraction and the other phase becomes the reinforcing phase. And the reinforcing phase can be distributed in either random manner or in some particular fashion. So, let us put it in words material consisting of two or more distinct phases.

And the two phases are usually termed as matrix and reinforcement. But why do we make a composite? Why do we want to combine two or more materials? It is to improve certain properties and but mostly mechanical properties. So, the idea of making a composite is to get the good properties from the two different materials and combine them in a way that you can get the best of both the words.

Now the question is when we are saying two or more distinct phases one question is can we also call aluminium alloys where precipitate is a distinct phase as a composite? And the answer is no. Like I said, one of the primary motivations of composites is to improve mechanical properties and one of these properties that changes distinctly is elastic modulus. So, as a general rule of thumb you can say that a system would be called a composite only when it has sufficiently different elastic modulus.

So, in the case of aluminium alloys you would see that pure aluminium versus aluminium alloy does not have very different elastic modulus. And therefore, we cannot term it as a composite.

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So, what will be the overall characteristics of properties of the composite dependent on? So, characteristics of course the two phases. So, what are the two phases? The two phases are matrix and the reinforcement not only these two but also the interface between the two. So, this part we will not talk much about in this particular lecture. You will see when we talk about toughening at that point you would see the importance of interface.

So, in general in the conventional sense composite material consists of two phases where there is a primary phase and a secondary phase. And the primary phase forms the matrix phase and the secondary phase are embedded inside it. And depending upon what is the material of the matrix or the primary phase we can overall have three different classes of composites. And they will be metal matrix, ceramic matrix and polymer matrix. In fact, these are the three main classes of materials.

And therefore, we can also draw a vein diagram to describe the different types of composites you will obtain. So, one of them is metals, ceramics and polymers. So, you can have polymer matrix where you can have the reinforcement phases as ceramic and metals or you can have ceramic matrix where you can have reinforcement phases polymer metals or you can have metal matrix where you can have polymer or ceramics as reinforcement.

But this is not all you can also have metal matrix with metal reinforcement. You can have polymer matrix with polymer reinforcement theoretically I mean not all of them would be meaningful as you would see in the next table. But it is possible and similarly you can have ceramic matrix with ceramic reinforcement.

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So, based on that we can describe the overall matrix of composites like this where you have primary phases here, metal ceramic polymer and secondary phases as metal ceramic and polymer. So, you can have combination of metal matrix, metal reinforcement. So, for example powder metal parts infiltrated with a second metal or you can have a ceramic matrix with metal reinforcement. But this is very rare because the overall characteristics of ceramics are brittle.

And therefore, if you use it as a matrix then the component will be brittle in nature. And therefore, it is not common and there may be very exceptional examples for this. And other possibilities of having polymer matrix and metal reinforcement and so on and as you can see combination with ceramic matrix is very rare because as I said ceramic matrix or ceramic in itself is brittle. So, having them as matrix would cause the brittleness to remain in the material.

And therefore, it will have a tendency to fail. But then there are also something as ceramic matrix and ceramic reinforcement. And this is particularly done to improve the toughness of ceramics. So, this is also something that you would get to see in the next part or part 2 of this course. Metal matrix is one of the most common ones. Now let us also look at other than these 3 there is also a possibility of having something like carbon-carbon composites.

So, example would be carbon fibres in graphite matrix and these are one of the highest strength materials which are used in some very difficult application like brakes for airplane and so on used in the noses of the wings of the airplane. So, used in nose meaning the part which experiences highest heat and stress of the wings, brake plates of airplane. And the characteristics of such composites are very high temperature resistance and wear resistance.

So, as long as the impact is low then it has good toughness. But at very high impacts they do not have good toughness. So, there are limitations apart from these some very good characteristics. So, this is a classification of composites based on what are the types of material being used.

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But you can also describe the composites in terms of based on distribution of reinforcement. So, what do we mean by distribution of reinforcement? So, for example if you have very small type of reinforcements then they would be discontinuous. So, you can have discontinuous reinforcements or if they are very long then it will be continuous throughout the matrix from one end to another end very long.

So, this is another classification of composites then you can also have types of composites based on the type of reinforcement. So, this is on the distribution. Now what we will define is on type of reinforcement. So, for example you can have a composite where you have particle distributed all over it. So, these are particle reinforced composites or you can have continuous fibres. So, the fibres may run from one end to the other end. So, this would be a continuous fibre reinforcement.

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And you can also have very short fibres or whiskers you cannot have very long whiskers. So, they would always be very small in size and they can also be used for reinforcements. Now in this context you would see later on that orientation of these reinforcement phases will also be important. So, this is short fibre or whisker reinforced. And lastly one very different class of composite is when you have laminates.

So, this is something that you would have seen in ply boards that are used for making furniture. So, different types of furniture that may be at your home if you look closely some of these are made by plywood’s and these plywood’s are like laminates. So, you will also have different type of materials apart from plywood. But this is one very commonly found material. So, this one would be named as particle reinforced composites. This would be continuous fibre composites.

This would be short fibre or whisker reinforced composites and this is laminate composites. So, this is the overall classification of the composites. Now let us look at what will be the role or what is the expected contribution from these matrix phases and the reinforcement phases.

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Role of matrix phase and based on this you would see why we do not use so many ceramic matrix composites. So, the purpose of the matrix phase one of the primary purpose is to provide the bulk form. Now if the bulk form is from the ceramic, then of course it being brittle in nature will also impart that brittle to the component. The purpose of matrix is also to hold and protect the reinforcing phases. So, because the; reinforcing phases are embedded inside it.

So, the matrix is also supposed to hold and protect that reinforcing phases. Shear the load with the reinforcing phase. So, this is now coming to the characteristics why we are actually making the composite in the first place because we want to improve the overall mechanical characteristics. And in that sense when you are putting the load, we want the reinforcing phase to carry the load. That way you will be able to carry higher load with the inclusion of these reinforcing phases.

So, shear the load now you can see the word shear. So, part of the load will go to the reinforcing phase. And when you do any deformation then the matrix is supposed to also take a little bit of strain. So, that the; load can be effectively transferred to the reinforcing. So, deform partly for effective load transfer. Now let us look at these are the role or the purpose of a matrix in composite. Now let us look at what are the roles that the reinforcing phase is supposed to play.

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So, like we said that we put the reinforcing phase primarily for some mechanical strengthening and therefore the primary purpose of the reinforcing phase is to provide reinforcement. As the name also suggests we provide reinforcement by carrying the bulk of the load. And whenever we put in the secondary phase or the reinforcing phase, we expect that it bonds well with the matrix. If it does not bond well then it will not be able to carry the load.

So, the other secondary role of the reinforcing phase is to ensure good bonding with the matrix. So, overall, the roles of the matrix and reinforcing phases are clearly understood. And accordingly, we include the material for either the matrix phase or the reinforcing phase.

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So, for example for the matrix if we are using metal then we know that metals are one of the most versatile engineering materials with very good strength, ductility and impact strength. So, if you want to utilize those properties then we would use metal as the matrix. But then the drawback of metals is that they are very heavy in the sense they are very high density. So, one of the purpose of adding the reinforcement phase could be to reduce the weight.

In which case you would include something like polymer or a lightweight metal which will result in improved specific strength. So, if it is a metal then we know that metals have very good strength but it is also high intensity. So, the purpose of secondary phase can be to reduce or to improve specific strength. Objective for using metal matrix and using a secondary phase is also to increase E or more precisely E by rho.

And in some application, you may have to increase E by rho square or sometimes E by rho q. And that depends upon this application and what are the primary objectives or the primary mechanical characteristics of the component that is being used over there? So, if the primary characteristics is such that E by rho is to be optimized then you will increase the E by rho or for some material it can be for some component or some application it can be E by rho square or it can be E by rho q.

Now let us look at the other option for matrix material which can be ceramic or glasses like we said that ceramic or glasses are very brittle in nature and because of that it is very less common to use ceramic as the matrix phase. So, less common but still some places you may find use of ceramic matrix and that would be because they are very good insulators and also very chemically inert. So, in some cases where you want to use the materials where you want to have good insulation.

Or you want to use it in a chemically active environment then ceramic matrix composites would become a good choice. And you will have to strengthen it with secondary phase which will improve its toughness because we know the weakness of the composite is toughness. So, the secondary phase would be used in a way that it improves the toughness. The third possibility is polymers.

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The good qualities of polymers are good ductility insulating properties. But on the other hand, they have low strength and creep resistance. So, the purpose of reinforcement in such composites would be to improve these properties. So, for example you can think of the lights that we use for Diwali nowadays: the wire that you have over there, the polymer is providing the insulation and inside the aluminium alloy or what aluminium wire that is providing the current.

Now here the reinforcement is the aluminium or the copper wire whatever is being used for the conductivity while polymer is being used for insulation. And at the same time, it is also providing the ductility during the formation and the load is being actually taken also by the polymer. So, in that way you are able to reduce the overall amount of aluminium or copper that you have to use and thereby you reduce the cost.

If you look at the older type of wires which were used you would see that the aluminium or the copper, they were much thicker. Because over there the; purpose was not only conductivity of the aluminium and copper but also to provide the overall strength. But nowadays to reduce the cost manufacturing has been optimized so that polymer is the primary load carrying component over there.

Now polymers have also low density and hence this can also be used as reinforcement for the purpose of light weighting. But then that would be when you are using polymers as a reinforcement but when the polymer resorts itself the matrix then you do not need to add any more polymer to lightweight. It is already very lightweight. Now let us look at the reinforcing phase.

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So, the reinforcing phase we can have different types of materials and the reinforcing four phases as we have seen can exist in various forms. So, what are those various forms? Some of these we have already seen like fibres, long strands with circular or non-circular cross sections. But constant cross sections we should say and where the diameters can range from few microns to fraction of millimetre. So, you can have fibres like this.

Or you can have particles particulate shaped again ranging from few microns to fraction of millimetre or you can have flakes two dimensional particles like platelets. So, they can also serve as reinforcing phase or you can have infiltrated phases. So, for example the primary phase may have lot of porosity and the secondary phase can infiltrate. So, when the secondary phase acts like a filler in the matrix then it is an infiltrated phase.

And this is usually found in powder metallurgy. Fibres are usually tubular or rectangular or it can sometimes also be hexagonal. But the important thing is that usually they will have constant cross section. And fibres can bear the majority of the load. So, they act as a very good load sharing component in the composite. Filament structures of fibres are mostly defect free. If you look at very thin metals, they are usually dislocation of free also which are called whiskers.

And similarly, the fibres are also mostly defect free and hence they have very high strength and that is why they can be used as reinforcement. Now you can have it as continuous or it can also be discontinuous. So, you can have very long fibres or you can have very small fibres. And then thickness can also vary if the thickness is very small you can have something like whiskers which can have diameter as small as 1 micron.

On the other hand, you can have very thick fibres which will not be viscous but they can still provide good reinforcement. Fibre reinforcement is also an important parameter in determining the overall strength of the material. So, now whatever you are using, like if you are using the fibres then the length the diameter everything actually makes a difference to the overall properties. So, here is an example if you change the fibre diameter if you keep increasing the fibre diameter.

Then what happens to the overall strength of the material of the composite. You see that the strength actually reduces. So, this schematic is showing that strength will reduce as the diameter of the fibre increases and that is because as the diameter of the fibre increases it becomes more prone to having defects. On the other hand, if it is very small or very fine diameter then it will not have too many defects and in that case the fibre themselves will have very high strength.

And therefore, it will also be able to carry much higher load. So, this is the tensile strength of the fibres not the composite. So, this is the tensile strength of the fibres and you can see that as the diameter increases it is reducing it is becoming more and more prone to having defects this is one thing.

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Another factor that affects the strength is how the fibres are oriented. So, for example here it is long continuous fibre here it is fibres oriented along two different directions or in this case it is very small fibre. So, the length of the fibre is one thing that will make a difference. And second is in the case of small fibres how they are oriented. So, are they oriented randomly or if you are applying the load like this? So, how close are the small fibres with respect to the loading direction.

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And that is explained in this figure. So, here is the elastic modulus on the y axis and here is the fibre angle. So, on an average if all the fibres are along the direction of loading, then you can see the elastic modulus is very high. But if the fibres are oriented away and further away from the direction of loading direction you can see that the elastic modulus of the composite decreases. So, this is showing the elastic modulus of the composite.

And this is showing the effect of fibre orientation. Articulates of metals and ceramics can also be used as reinforcing phase. For example, you may have seen or you may have heard of cermet.

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So, cermet is coming from ceramics and metals. So, here metal is the matrix and ceramic particulates are added into the metal matrix and the purpose is to improve wear resistance. So, metals are very good, have very good strength, very good toughness but ceramics have much better wear resistance. And therefore, when you add ceramics into metal matrix you can get very good toughness as well as very good wear resistance.

Distribution of particles that we have already seen in the case of fibre. But it is also true for particles whether it is randomly distributed or homogeneously distributed that will determine the overall properties of the composite. So, if it is homogeneously distributed one thing you can expect is that the properties would be isotropic in nature. Strengthening also depends on particle size. So, small particles cause strengthening by dispersion hardening and improving the load carrying capacity of matrix.

On the other hand, larger particles share the load with the matrix and proper bonding is very important in the case of larger particles. And they are able to transfer the load from the matrix to the reinforcing phase. So, the overall role of the reinforcing phase remains same. But then if the mechanism changes whether it is a small particle small in the case of small particles it will improve the strength by dispersion hardening.

And in the case of very large particles, it will improve the load by sharing the load with the matrix. Now we will move on to the strengthening mechanisms in the composites.

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So, there are two different two broad mechanisms of strengthening. So, we have already looked at it in a very broad way. Now we will look at it in a more specific way. So, there is direct strengthening and then there is indirect strengthening. So, direct strengthening is what we already know that there is a load transfer due to load from matrix to fibre. So, here is a schematic which explains. So, let us say this is the fibre and this rest of it is matrix.

And the lines are just shown as iso-stress conditions. So, initially when it is unstressed then of course every point is at 0 stress and all of them are showing 0 stress. But when you apply a stress like in the directions shown over here then there is iso-stress line this here, over here. And you see now because of the presence of this particle or the fibre the stress contours have changed and this is how the stress contours look like.

And this is because the small amount of actually not a small amount but a very large amount of load is being now carried by this fibre. And therefore, the stress contour looks something like this. So, this is what will be called as direct strengthening where there is difference in local displacement which leads to shear stress at the interface. So, there is a difference in the local displacement from this point to this point and this will also lead to shear stresses at the interface.

And that is where we said that bonding between the fibre and the matrix must be very good. Now let us look at what is indirect strength?

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So, this happens when there is a change in the matrix microstructure and properties due to addition of reinforcement. So, this trending is happening via the microstructure. So, first there is change in the matrix microstructure and hence the properties due to reinforcement. This can be explained via two different routes. So, one case or two examples. So, let us say in one case your matrix has higher CTE or coefficient of thermal expansion and reinforcement has lower CTE.

Now if you heat this kind of material then what will happen? What will happen is that there will be stresses generated near the interface and because of those stresses dislocation would get generated at the interface. Stresses and hence dislocations generated at interface. So, you can see that now you have dislocation. And you remember when there is dislocation density increases then there is a strengthening.

So, this is dislocation interaction strengthening or you can say strain hardening. Because there is now strain in the region and that leads to straining in the composite. The other application or the other example that you can think of is what will happen to the grain sizes compared to the unreinforced matrix. And you will realize that the grain sizes would also reduce and this would lead to grain size strengthening.

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And if you look in the literature you can find that if you have a matrix and if you put a fibre something like this. So, let us say this is the fibre and rest of it is matrix then people have shown that if you do etching which shows the dislocation near this region then you would clearly see that there are much larger density of dislocation near this. So, this is one thing the other if you look through literature of metal matrix composites you will see that if there are particles that are formed somewhere.

Then because there are particles generated near because there are particles there will be stress in the region and therefore, new grains form and you can clearly see small grains near these are called particle simulated nucleation and away from it you would see the grains are what you had originally. So, this is again grains so, this is the example of the first one where dislocation density has increased.

And this is the example for the second one where strengthening has taken place because of grain refinement. So, we will look at another aspect of composite which is the elastic properties of composite in the last part of this lecture.

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$$\boldsymbol{\rho_c = \frac{m_c}{V_c} = \frac{m_m + m_f}{V_c}}$$

Type equation here.

So, let us move on to elastic properties of the composites. So, now we know that in the composite you have the matrix as well as the reinforcement. So, one thing that we can clearly write is that the mass of the composite would be equal to mass of the matrix + mass of the reinforcement. Now when we; come to volume so matrix and reinforcement are of course there. But then along with that there may also be some defects or voids. So, you also have to take the volume of those voids.

So, that will form the total volume of the composite. Of course, voids do not have mass and that is why it is not added in the previous equation. Now based on this we can say that the density of the composite = m c by V c which is equal to m m + m r by V c where V c also includes voids.

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$$\boldsymbol{\rho_c = \frac{m_c}{V_c} = \frac{m_m + m_f}{V_c}}$$

And in terms of the density of the matrix and density of the reinforcement we can write mass of the matrix and mass of the reinforcement in this form m m, rho m, V m and m r = rho r V r and therefore, when you put it in the equation over here so here you replace m m by this equation and m r by this equation. And we know V m by V c would be termed as f m which is here and V r by V c would be termed as f r which is fraction of the reinforcement and fraction of the matrix.

Then the overall equation would form like this and this gives you the rule of mixture for density. You do not have to individually weigh the mass of the matrix and the mass of the reinforcement. You just need to know the fraction, the mass fraction and the reinforcement fraction. And if you know that and you know the density of the matrix and the density of the reinforcement you can obtain the density of the composite.

And here we have to keep in mind that V c also includes the volume of the voids. In case the volume of the void is negligible then of course this becomes much simpler V m + V r would be = 1. But if there is sufficient amount of void then V m + V r + V v will be = 1.

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$$E_c = f_m E_m + f_r E_r$$

Now coming to some of the properties of the composite which are the very fundamental properties. So, now here you have to realize that how we load the composite will determine how the stress is being shared. So, with that respect, yes, this particular arrangement where you have one matrix and the other has the reinforcement you need not have the equal fraction of filler. It is just for the sake of simplicity that it has been drawn like this.

But what it is trying to show is that a strain when you apply a load in this fashion what will happen is that the strain in both the matrix and the reinforcement would be same and which is explained as or written as iso-strain model. And if you were to write it or to draw it as a resistance model then it would be shown like this where you have sigma being applied to this matrix and the reinforcement where both of them are in parallel.

So, if you apply then both of them will expand equally. And therefore, strain in the matrix as well as the strain in the reinforcement would be same. On the other hand, what happens here is that the strain in the matrix and the reinforcement will not be same. But in this case the stress that would be applied because now when you apply a stress it is same throughout from here to here. And therefore, the stress that is being applied to the matrix and the reinforcement is same.

And therefore, it is termed as iso-stress model and it can also be represented like this. So, here this is spring represents matrix and this spring represents reinforcement. And based on this we can have two extreme models for calculating the elastic modulus of the composite. So, when there is continuity in strain the model can be treated as set of spring in parallel arrangement and what you can see is that here E c would be equal to the rule of mixture f m E m + f r E r.

It is also termed as rule of mixture as the modulus is proportional to the volume fraction of each phase and as we will show later that this forms the upper bound that your modulus of the composite cannot be higher than this. We will not derive this but we will show it with in a schematic what it means by saying upper bound. So, it is a good measure or method for measuring the elastic modulus when along the direction of fibres.

So, this is the fibre here it has been shown as laminates but you could also have fibres running along this direction. So, if that were the orientation then this would be a good approximation to find the modulus of the composite. So, this is also called as Voigt model. The other one which is the iso-stress model is also called as reuse model and when the modulus is to be measured when the strain is not expected to be uniform as you can see in this particular case.

But stress is supposed to be constant then one can treat this model as a series and very easily you can show that E c I will put a prime here to show that it is perpendicular and different from the other one. The E c would be given by so I just noticed that I have written it as E f it should be E r actually reinforcement. So, there is a matrix and there is a reinforcement. This is matrix and this is reinforcement.

So, this would give you the elastic modulus when the load is being applied perpendicular to the orientation of the fibres. In this case what we get is actually the lower bound meaning the elastic modulus can never be below this for a composite. So, if you know the elastic modulus of the matrix and the reinforcement phase and their matrix fraction and the reinforcement volume fraction then your composite elastic modulus cannot be lower than this value.

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And this part is very neatly summed up in this figure. So, here is the rule of mixtures so, let us say this is on the y-axis you have elastic modulus. And on the x-axis, you have volume fraction of reinforcement which means 1 - matrix assuming that there is no Voigt volume fraction or if the Voigt is also there then this will become 1 - V m - V v. So, here the reinforcement phase is increasing and this is the elastic modulus of the reinforcement.

And as you would expect; that reinforcement will have higher elastic modulus. That is the purpose of the reinforcement and the module matrix as the lower elastic modulus. And if you have the parallel configuration which is called the Voigt model then you get a rule of mixture a straight line like this. And if the load is being applied in the perpendicular direction so here it is the schematic. So, this is the reinforcement.

If you allow apply along these lines then it is the Voigt model and when you apply a perpendicular to the reinforcement this is called reuse model and it is over here. So, this gives you the upper bound and this gives you the lower bound. So, what this figure is telling you is that if the volume fraction of the reinforcement is let us say somewhere over here then the elastic modulus would lie in this region. So, this would be the lowest value, this would be the highest value.

That is the meaning of lower bound and upper bound. Depending on how the reinforcements are distributed. So, no matter how it is distributed it will never go beyond this and no matter how it is distributed it will never go below this. And in that sense, this is the lower bound and this is the upper bound. And this is giving you the orientation. So, if it is completely continuous reinforcement fibres something like this and you are applying the load like this.

Then this is your E c which would be the white model meaning parallel. So, this is iso-strain condition. The strain in the fibre is same as the strain in the matrix. And if you are applying load like this meaning the fibres are perpendicular to this then this would be iso-stress condition. And it would be more like the series condition and the stress is constant not the strain. And in that case, this would be the value. So, these are the values for these two extreme conditions.

And other condition could be you have smaller fibres and they are oriented in various directions and so on. So, no matter what it would be in between these two. So, that completes our basic understanding or introduction of composites. And in this also completes our mechanical behaviour of materials part 1 course. So, thank you and the next part would consist of primarily fracture fatigue entry which will also deal with composites and ceramics.

So, for next level of mechanical behaviour of materials or the second part of this please register for that course. Thank you.