Analysis and Design of Bituminous Pavements
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Lecture - 08
Introduction to KENLAYER

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So, let us continue our discussion and in fact professor Padmarekha will walk you through how to use the KENLAYER computer program. But what I am going to do is to give you some snippets about how such computer programs are actually designed to solve this n-layer problems. Now, first and foremost thing, we need to understand this very very carefully because these are the keywords here, elastic multilayer. So this entire pavement analysis and design framework depends on assuming all the layers of the pavement follow linearized elastic response. So that means everything has to be given in terms of Young's modulus and Poisson's ratio. Later, when you are doing the material characterization or in fact if you have taken our course on mechanical characterization of bituminous material, you would have noticed that we talk about bituminous material as viscoelastic material. And when we are talking about the material characterization in this course we will also be saying that the granular materials show pressure dependent response. So, both of them are definitely not elastic in nature, definitely not linearized elastic in nature. So, what this means is we will be using some kind of a surrogate modulus here. So that needs to be very clearly understood. So, when we say something like the surrogate modulus what we really mean is the following, that they are not really true elastic modulus but they seem to be having this notion of an elastic modulus. Now, second thing is this multilayer. So when we say multilayer, what we really mean is we are not going to restrict our attention only to 3 layers because when we used this charts and computed the stresses and strains we were probably talking about 1 or 2 or at best 3. In fact, we did not solve any problem with the 3 layers because they involve number of charts and tables and so on and so forth. So we restricted our attention only to 1 layer and 2 layer. So now coming back to this, since we are using a computer program what we can actually do here is, we can solve for as many number of layers as possible. First and foremost thing is all the solutions that you are seeing will appeal to axis symmetry. The second thing that we need to understand is, we are going to assume some kind of a stress function for all the vertical layers, σ_z. And the third thing is there is a vertical stress under the circular loaded area and finally, the boundary conditions or the interface conditions that you are going to see here consist of continuity of vertical stress, displacement, shear stress and radial displacement at (n-1) interfaces. So that means if there are n interfaces, let us say what you are going to do is if you can compute any value at the bottom of this layer and compare it with the similar value at the top of the next interface, they should be identical. So that is the whole idea here.

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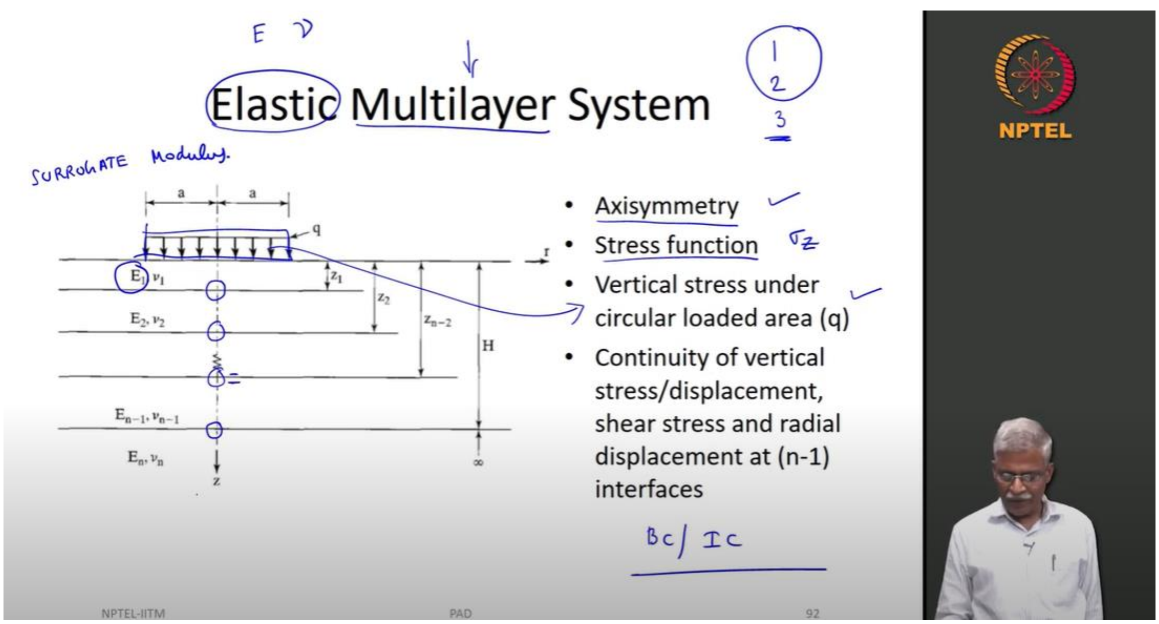

Now let us start talking in terms of superposition of wheel loads. Now what we really need to do is as of now, whatever problems that we solved till now looked at something like this. Now in the plan view, let us say, you know you are talking about x and y, you have what I call as dual tandem. So, that means we need to understand this, there is one axle, there is another axle, we are talking about 2 wheels here, 2 wheels here and mostly we will be focusing our attention on one side. So, that is what is shown in this picture now.

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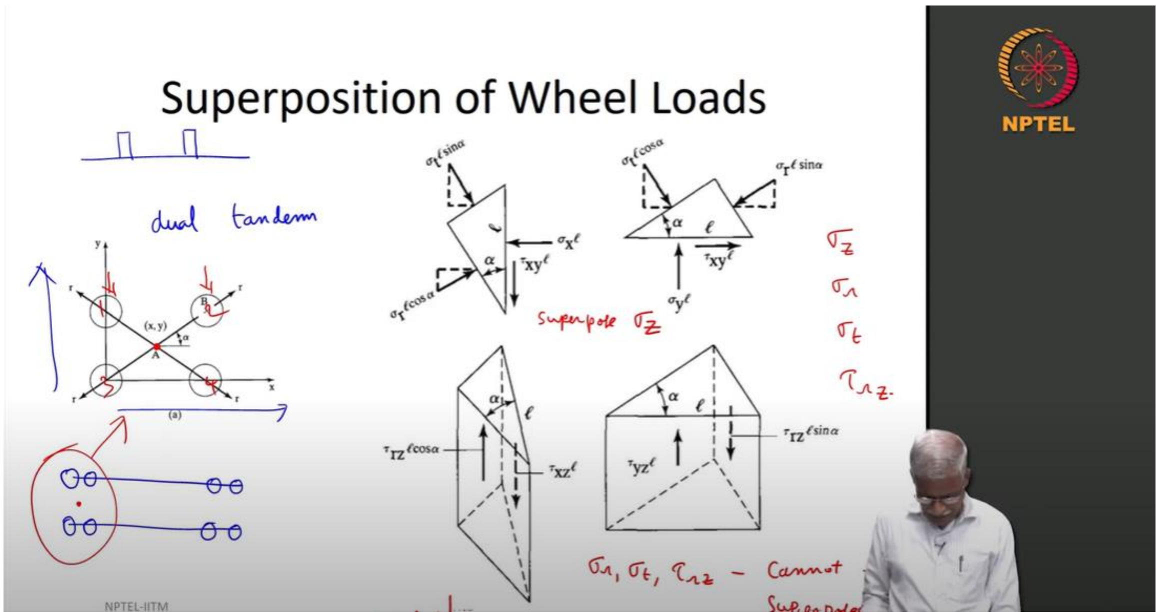

So, let us say, I am interested to find out the stresses and strain at any point A and so what do we really do? So, in fact we can resolve it. We have σ_z, σ_r, σ_t, τ_{rz}. So, we can basically resolve it but how can you resolve it or how can you even do the superposition? You can superpose σ_z. So that means the stress at this point A can be taken as the sum of the stresses at this point A due to these loads 1, 2, 3, 4 because they are all in the same direction.

So, you can do that but you really cannot do it for σ_r, σ_t and τ_{rz}. So σ_r, σ_t, τ_{rz} cannot be superposed. So, we need to resolve them basically, talk in terms of x and y and $\sin\theta$, $\cos\theta$ and all that stuff. So, when we do this, for this you are going to get $\sigma_r \cos^2\alpha + \sigma_t$ $\sin^2\alpha$, similarly for σ_y, similarly for τ_{xy}, similarly for τ_{yz}, similarly for τ_{xz}. So, you will be able to get all these things. Now what you really need to do is you need to now superpose it for multiple loads. So, you can do the superposition for multiple loads.

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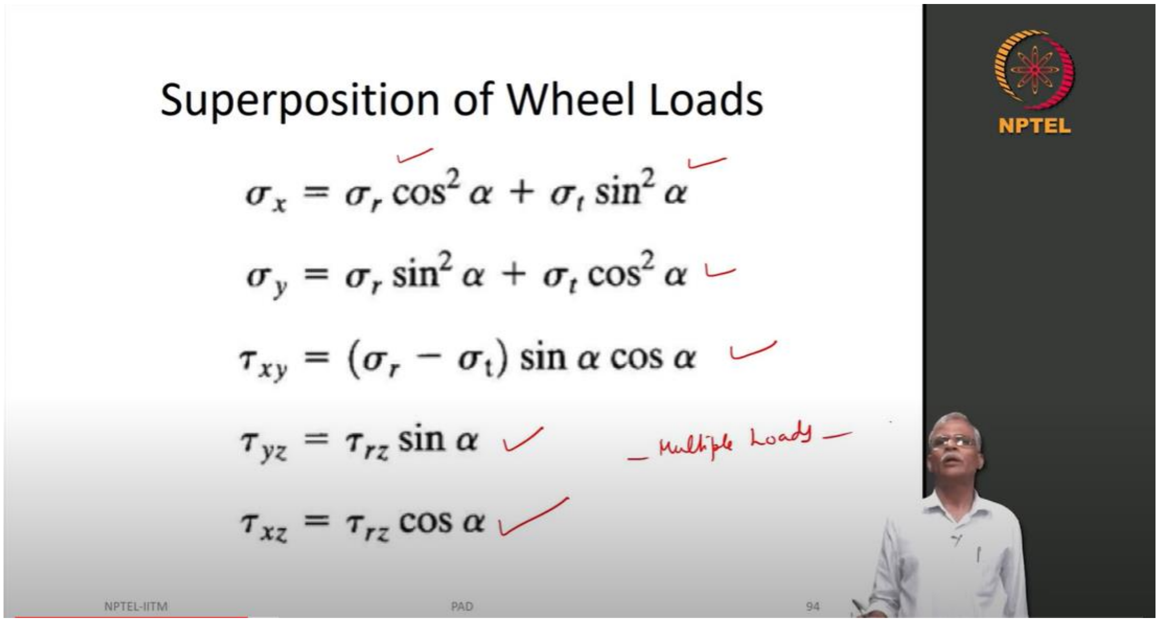

Once you have found out these values σ_x, σ_y, τ_{xy}, τ_{yz} and τ_{xz}, you can actually find out this characteristic equation. I think we have discussed this before and the roots of this equation basically will give you the principle stresses and the principle strains. So, σ_1, σ_2, σ_3 will be the roots of this particular equation. So how do we compute ε_1?

$$\varepsilon_1 = \frac{1}{E}(\sigma_1 - \upsilon(\sigma_2 + \sigma_3))$$

Similarly,

$$\varepsilon_2 = \frac{1}{E}(\sigma_2 - \upsilon(\sigma_1 + \sigma_3))$$

$$\varepsilon_3 = \frac{1}{E}(\sigma_3 - \upsilon(\sigma_1 + \sigma_2))$$

So these things can actually be written here and in the same way what you can actually do is ε_x as well as for ε_y also you can write.

$$\varepsilon_x = \frac{1}{E}(\sigma_x - \upsilon(\sigma_y + \sigma_z))$$

You can also write a similar expression for the shear strength. So, these are fairly standard strength of material that you would have been exposed to in your second year undergraduate degree in civil engineering.

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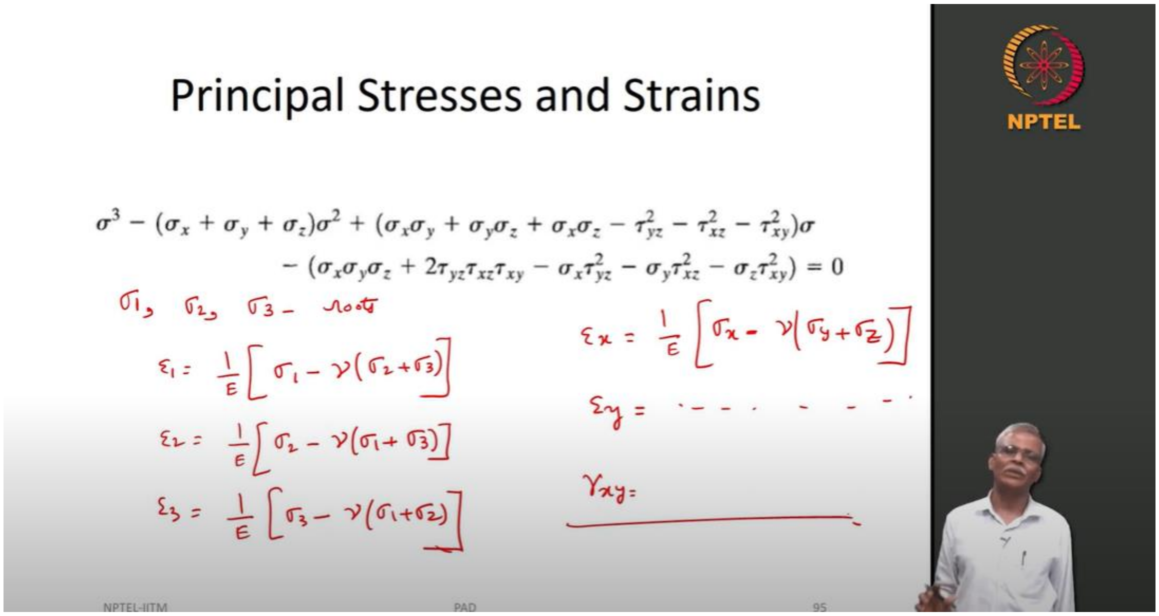

But, how is this being used here? Because, what we are looking at is from the plan view, there are 4 wheels here and at any given point below we need to compute the stresses and strains. So, σ_z is in the same direction so we can add it up. But, since you can actually see here $\sigma_t, \sigma_{tr}, \tau_{rz}$ are in different directions. You need to appropriately resolve them to the x as well as the y direction, add them together and then get it. So, once you have finished it then you can actually compute the various strains here. Now, what this KENLAYER program will do is exactly the same thing. So, that is what this KENLAYER program is going to do it for you because you can actually give as many tandem you can, even do the tridem.

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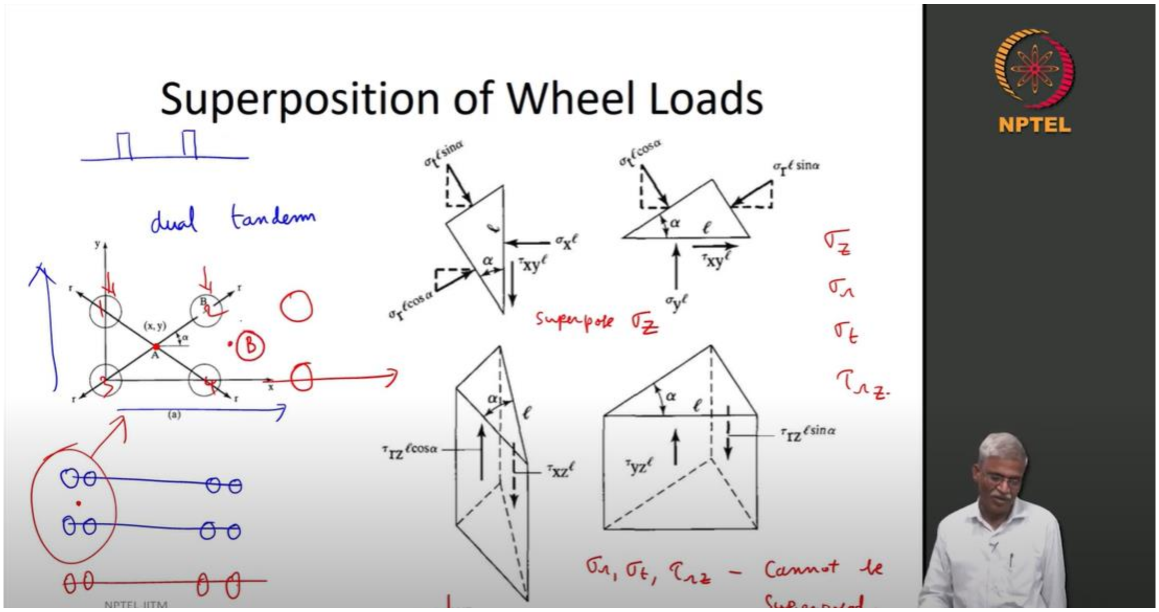

So in fact if you have tridem, so let me add so it is going to be, so let us extend this so you are going to be having something here and let us say we want at any point B somewhere in between, you need to keep doing the resolution and then add them together that is something that the software will also do.

So now comes the most important thing, because what do you really do here, you are going to use this to compute what is really called as the horizontal minor principle strain and in fact if you recollect your layer theory that we discussed earlier, we said this is bituminous layers, granular layers and subgrade so you are talking about 1, 2, 3 and here we said this is the one that is going to be critical as far as the fatigue is concerned and how to compute it and again this was discussed earlier also.

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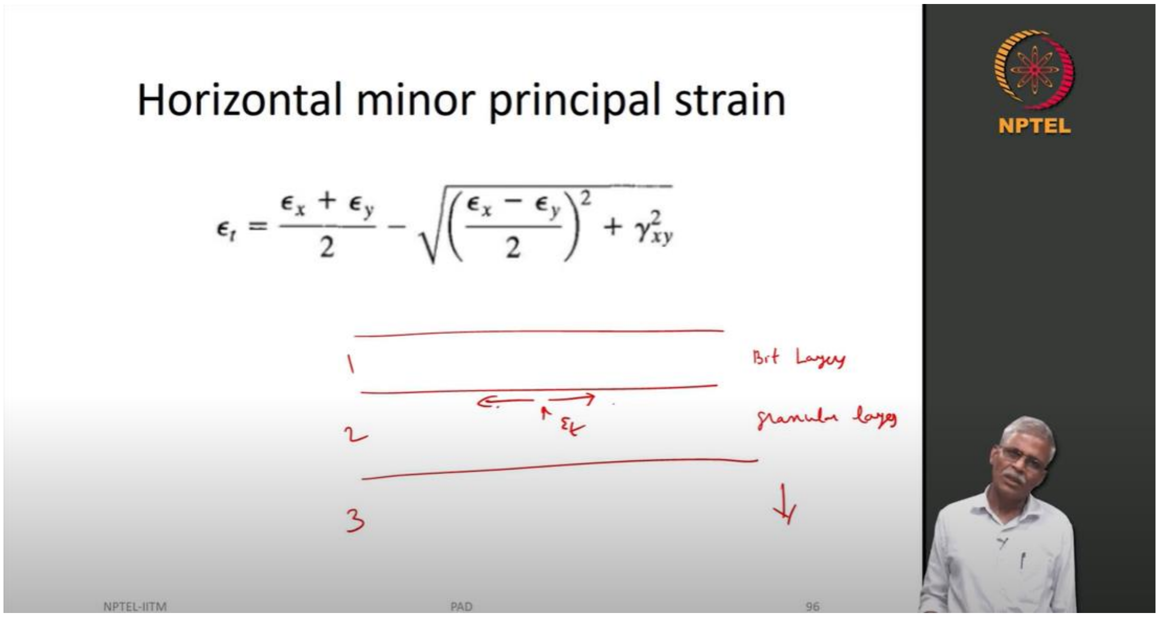

Now after having done all these things I am kind of slightly taking you ahead but when we do the pavement design these things will become very clear and you also recollect what we discussed in the first few classes about what are the various steps. The first step that we said was what are the input parameters. We said we need to know the bearing capacity of the soil, we said we need to know what is the material that we are going to use, we said we need to find out where we are going to lay the pavement and what is the axle load. So, after having collected all this information, what we do, we pick a cross section. I hope you remember all these steps we, pick a cross section. Now after having picked this cross section, we substitute this material parameters. So, I will just give a draw this thing here, so let us say this is the cross section I am just going to arbitrarily give some numbers. So, 40 mm of bituminous concrete (BC), 100 mm of dense bituminous macadam (DBM), 250 mm of wet mix macadam, 300 mm of sand gravel mix subbase and let us say there is a compacted subgrade of 500 mm. Now, this is the cross section, this is your trial section. Now what you are going to do is, we will be talking in terms of an 80 kN standard axle load and in fact Professor Neethu Roy will be telling you what is really called as equivalent single wheel load, equivalent wheel load factor, equivalent axle load and etc. So now, let us say we apply a load of this type 20 and 20 kN. In fact, what you typically have you are going to have 20 20 20 20 so this is 80 kN. There is a pressure of 560 kPa. Now you know very well that you want to compute the ε_t here (bottom of BC and DBM) and let us say we compute ε_c here (top of subgrade). Now, we apply this standard load, we compute this ε_t as well as ε_c and then we need to find out what is the expected load repetition that this particular cross section can take. That is the idea.

Now, of all these classes that we have been essentially talking about how to compute this stresses and strain. So now, that we know how to compute the stresses and strain we put this load here, we compute this stress and strain, substitute it here and also substitute the modulus value here. So you are going to get something called N_f. Now, what does this N_f basically tell you, it tells you the number of repetitions that this pavement cross section can take. Now, what is the point? The point is what is the target failure? So you are talking in terms of 10% cracked area. So, you substitute and you get, let us say 40 million standard axle load, ESAL value - equivalent standard axle load. Now, let us say your traffic predictions you know you do all the calculations related to this traffic prediction and for 5 years, the load is going to be something like 50 million standard axles, then you are basically going to say but this cross section can take only 40 million but I need 50 million so you will say that this cross section is no good. But on the other hand, if this cross section can take 60 million standard axle load but you have your traffic predictions are only 50 you will say that this cross section seems to be safe. So that is the general idea.

Now, why I am saying all these things? How do we compute this value, what is the load bearing capacity of a given pavement in terms of rutting, in terms of fatigue and for that these empirical expressions what I would really call as distress transfer functions are used here and so when I use my layer program, KENLAYER program and when I compute I will get these values. Now, I will just give some standard values that are followed in Asphalt Institute. This is for N_f, so it is going to be 0.0796, 3.291 (focus your attention on 3.291), 0.854. For N_d, this is related to damage you are going to get something like 1.365×10^{-9} and 4.477 (again pay close attention to these 2 numbers). So now the interesting part is this expression looks like regression equations. You know some kind of regression is done because these are all some parameters that are given here. So, if you have spent some time thinking about all these things and if you have worked out some problem, it should immediately occur to you as to why E_1 is also given. E_1 is related to ε_t, whatever is the strain that you are saying basically depends on the modulus value but not exactly true because what we are missing is the thickness. So as a function of thickness for any given modulus the ε_t values can vary non-linearly and so that is why we use also E_1 here and there is also some notion about thin pavement and thick pavement. So, using your ideas related to layer theory and following KENPAVE software you will substitute all the material parameters which are the input to compute what is the N_f, check it with your traffic prediction, if it is not matching, what you are going to do, you are going to redesign. That is the whole idea and this is where right now in this pavement design course. So, this is the important part about pavement design.

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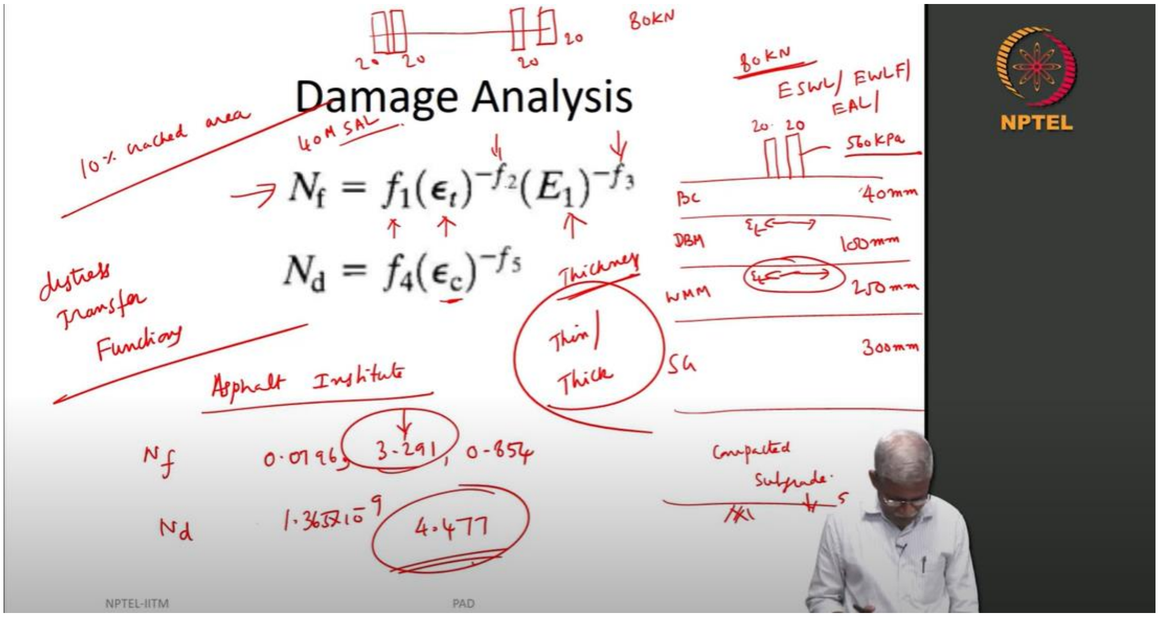

Now, how do we really compute damage? See this is going to be the problem. How to compute damage because if you are looking at the IRC kind of method that you follow for pavement design other than this particular thing you are not going to see anything else but on the other hand if I really want to find out what will be the damage if I am going to have let us say these kinds of sections say tandem axle dual wheel which is what I mentioned. So, we need to find out for this portion what is going to be the location of maximum strain. So, 80 kN is single axle dual wheel, 160 kilo Newton is tandem axle dual wheel, 240 kN is tridem axle dual wheel. So, you can have two ideas here. The first and the foremost thing is you can take split this and say that okay one passage of tandem is equivalent to two passages of 80 kN. So that means all I really need to do is to find out the location find out the strain and then do it. That could be one thing. Another thing that you can say is that is not really correct. I will just take this as one complete set because each of them is 80 kN and compute taking them as one passage. So, one passage of tandem is this equal to twice that of single. One passage of tridem is equal to thrice that of single. Is this true? No, it is not true. Both the extremes are not going to really work out. So how are we going to do it? So, what we will do? We will do it in a slightly different way and in fact that is how KENPAVE is also going to do and I advise all of you to just start playing around with this software and understand how it works.

So, what we can do is, take a look at this location 1, 2, 3, find out what is the maximum strain here. So, let us call this as ε_a, then move it to the center and find out what is the maximum strain. Let us call it as ε_b. So, what you need to do is, you need to take it in terms of $\varepsilon_a, \varepsilon_a - \varepsilon_b$ and ε_a, midway between these two axles and under the second axles. I would like you to think about this also, use KENPAVE judiciously and try and see whether you will understand it.

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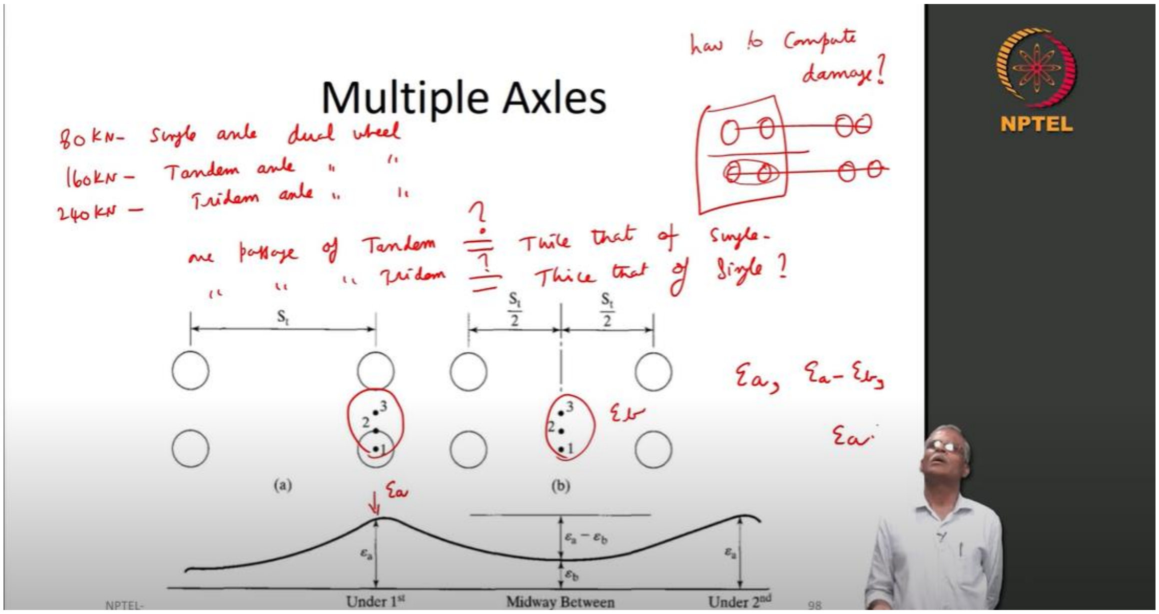

And then, from now on, what I am going to do is I am going to ask you to answer few questions, because now you have a software, it is going to generate lot of information to you and we want to ask some simple questions here. So, let us take a look at a simple thing, like for instance what we will do, we will just go to KENPAVE and then do this example problem. So, there is a single tire, there is a dual tire, now this is 4500 pounds, 4500 pounds, this is 9000 pounds, this is the contact radius here, E_1 E_2 values are given here, Poisson's ratio is given here, h_1 h_2 is given here.

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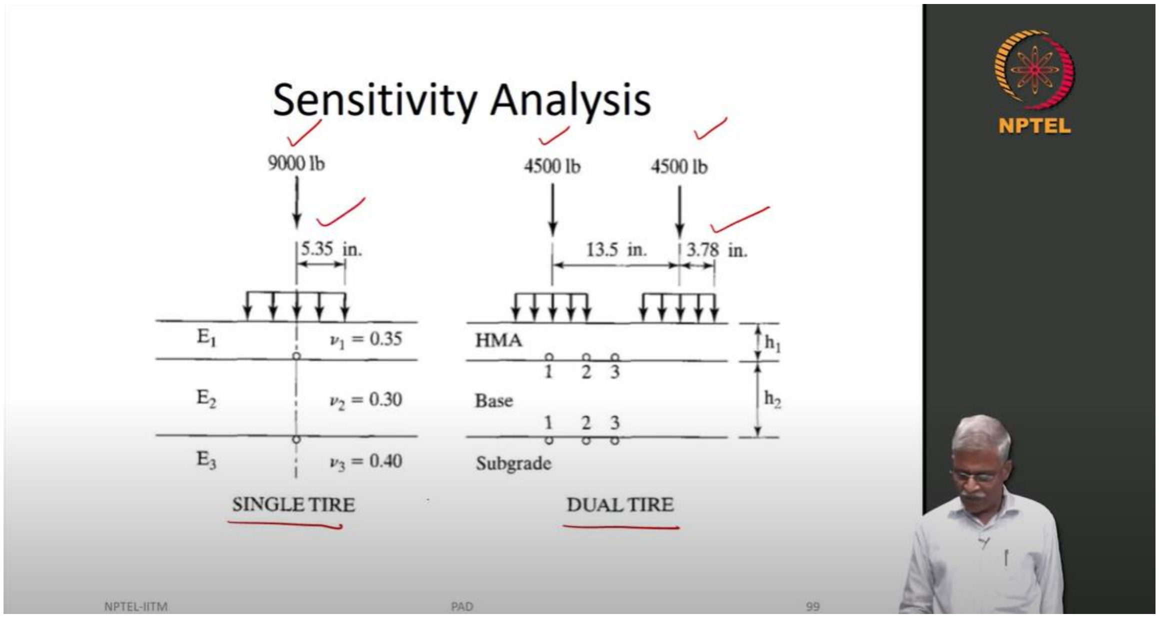

Now, what you see here is the ε_t values and ε_c values have been calculated for h_1 which you see here for various h_1 values, you can think in terms of 2, 4, 6 and 8 and h_2 is taken as 4 or 16 and one is for single another is for dual. So, lot of simulations have been done here and what I would really like you to do is to answer the following questions and in fact I just want you to look at this figure and try and see whether you can answer this question. Can we use single tire to replace dual tire? What do I mean by that? This is single tire, 9000 lb. Can we use this instead of these two things? That is something that you need to really answer. Now, what is the influence of thickness on dual wheel? Now you have to answer this question for ε_t and ε_c. Now, the answer to all these questions is provided in the text book which you should be having as a reference. My suggestion to you is to use this as an opportunity to go around and take a look at it.

Now, how to prolong the fatigue life? So, what do I mean by this? So let us say the E_1 values E_2, E_3 are given here, they are all taken constant. What is varied? h_1 value is varied, h_2 value is varied. Now, if you really want to prolong the fatigue life, this is what you need to really use. So, now the question that you really want to ask is, if I use a high h_1 and you can even say in this one h_2, 16 inches. So, if you use this combination in dual, you are going to get a much lower strain which means much higher fatigue life. But will anybody in the right sense use for the topmost layer 8 inches of thickness, they will not do it. So, you may want to really talk in terms of 2 inches. Now, the interesting part that you see here is this portion. So, looks like whether you use this thickness or this thickness here, this value seems to be more or less identical. You need to really think about this, why is this happening? So, in fact what you will do you will use these values, substitute it here to compute your N_f values. So, how to prolong the fatigue life? How to prolong rutting life? So you are given combinations of h_1, combinations of h_1 and h_2 and you are also asked whether you want it to be single and dual. So, take a look at these figures, that are given above and try and see whether you can answer this question. And so, when you go through this chapter 3 of this book, there are many such sensitivity analysis that has really been worked out. So, it is up to you to understand each of them but we will help you if you have any question, just put it in the chat and we will be able to understand that. Now one last concept that I need to introduce before professor Padma takes over and walks you through the whole KENPAVE software is the following.

What exactly is this linearity, nonlinearity and the material modulus? Now throughout this course whether you are using IRC 37, AASHTO, old AASHTO (1993), you are going to be talking about resilient modulus for granular material as well as resilient modulus for bituminous material. Now, if you really need to know something about this resilient modulus of bituminous material, what you need to do is to go take a look at our old course on mechanical characterization of bituminous material that is already available in the NPTEL program. So, right now, you only talk in terms of E_1, E_2, E_3 and so on. So, what do this E_1, E_2, E_3 mean? They are what are called as surrogate modulus. So, the actual material shows some other response. So, we just need to capture something out of it in a sense called as resilient modulus. So, there is going to be a concept of resilient modulus, that is used here and in fact this will be discussed in detail in the material characterization part. So here, we assume something like shake down, shake down is going to really happen. So, how do you use them within the context of this layer theory?

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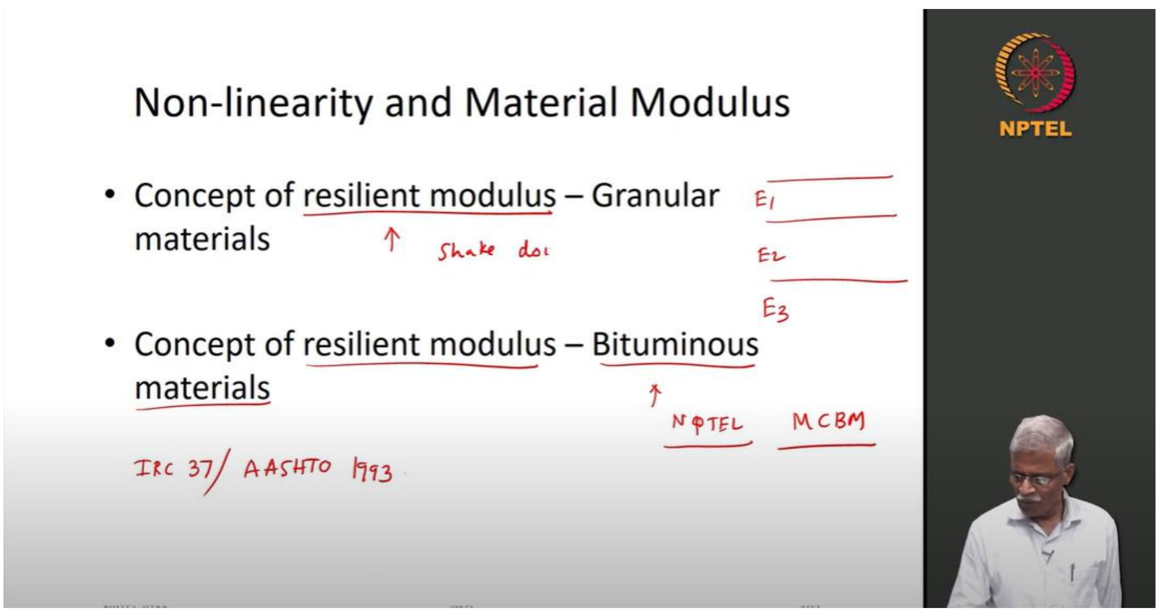

So, you can actually do it in different ways. So, one way you can do is, to split them into different layers. So, instead of using one layer, you can have E_1, E_2, E_3, E_4, E_5 and which can be assumed to vary in one specific way because you know originally when we stated our assumptions related to layer theory, we said the self-weight of the layers are not really taken into account. So, the easiest way in which we can do is to write something like this, $E = E_0(1 + \beta\theta)$. Now, what exactly is this θ? θ is nothing but your stress invariant but some soil mechanics related due to the coefficient of earth pressure at rest also will come. So, this is going to be $\sigma_z + \sigma_r + \sigma_t + \gamma z(1 + 2k_0)$, γ is the unit weight. z is the height at which you are looking at. Now, k_0 is the coefficient of earth pressure at rest. So, this is the starting value but the solution here is going to be iterative in nature. Why it will be iterative in nature? I will assume some ε. So, let us solve a simple problem. We will do one layer and let us take a look at some point where we are interested to compute it. So, I will assume some E_0 and then compute at this point $\sigma_z, \sigma_r, \sigma_t$ and then what I will really do here is to substitute the value here. Now, what exactly is this β? You can think of it in terms of how the modulus value varies as a function of the earth pressure, the summation of the principle stresses what is really called as θ here. So now, knowing this and substituting here you are going to get one more E here. Let us call it as E_1. Anyway, this is one layer theory so do not get worried about three layer theory. Then, we substitute the new E , so we substitute the value and then get a new E_2 and then you keep doing it till such a time E_n is approximately equal to $E_n - 1$. So now this becomes really tedious and you have to do it for every spacial point in which you want the stresses and strains to be computed. So, this is the so-called nonlinearity that is discussed here.

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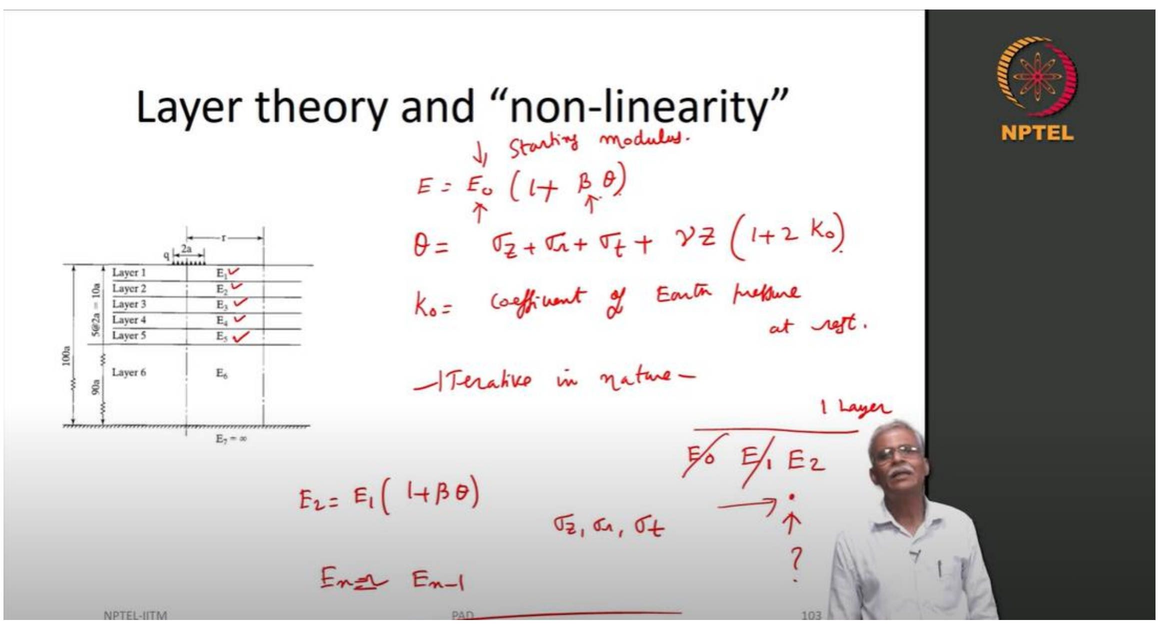

So, I will stop here. Thank you so much.