Introduction to Civil Engineering Profession

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Lecture – 13
Structural Modeling

So welcome to Introduction to Civil Engineering part of the lecture on Structural Modeling. I am Dr. Pradeep Pratapa some of you might know me I am a faculty in structural engineering here at IIT Madras in the Department of Civil Engineering. So, today we will be looking at some part of structural engineering and mechanics which is called structural modeling.

So, in this lecture what we will see is we will first understand, we will look at some examples of modeling and simulation and what modeling and simulation actually means. And what does it mean in the context of structural engineering and mechanics we look at a very simple example in terms of what you actually know, from before you came to IIT.

And then see how that transforms into computer models and how does it help to solve huge problems. So, huge solve complex problems in civil engineering and structural engineering. And then we will also see after that how this structural modeling can enable to venture beyond the horizon issue which we already know that is; maybe discover new types of structures, new types of materials model new kinds of structures which you have not envisioned before and all that.

And then we will see how it is kind of changing the phase of innovation and technology and all that in the end ok.

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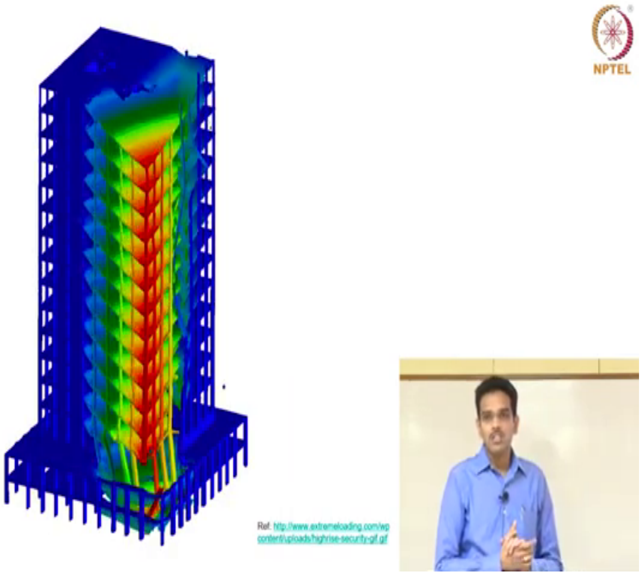

So, let us start. So, here I have an animation or simulation, computation of a computational model you can see that it is a model for blast loading in a building. So, what is exactly happening if you notice, is at the bottom there is a blast.

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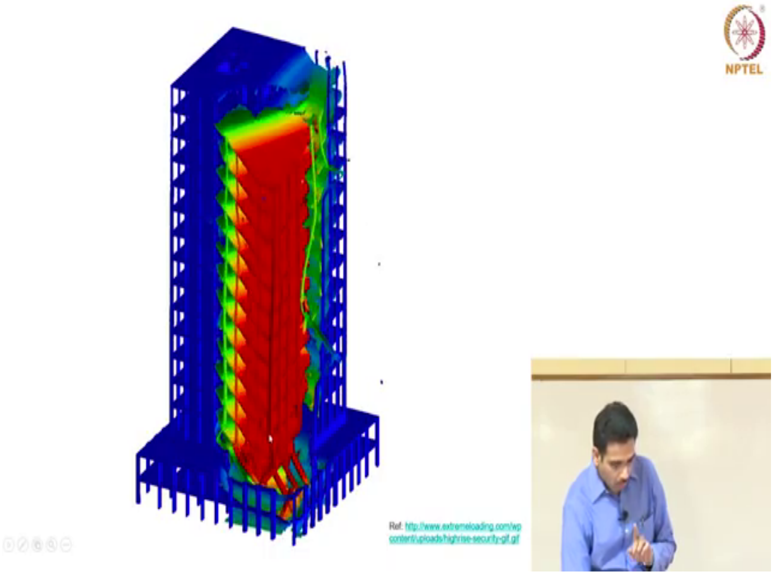

And a column at one of the corners this column starts failing and that leads to a progressive collapse towards upwards each slab and each of the structural elements in the slab keep collapsing and then there is a collapse of the entire section of the building. So, these kind of things can be studied well in advance even before such things happen, you can try to predict how a building might fail if there is a blast load.

And then maybe try to strengthen the building or different cases and come up with innovative designs.

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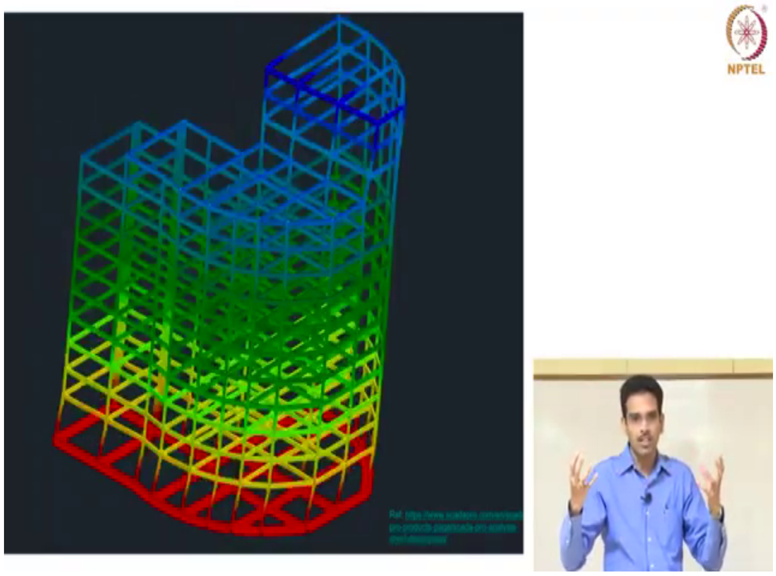

And this is another simulation of a building subjected to earthquake loads. So, what is an earthquake load? An earthquake is where the ground shakes. So, in this case we are looking at a ground shaking happening in a lateral horizontal direction and then you have a simulation of a structure which is on the ground.

So, you can study how the forces or deflections of the members of the structure are varying has a ground is shaking. And this give this will give you a sense of what is a maximum stresses or forces that my structure can take is it good enough will it be safe and if it is not can I maybe resize my structures like for example, can I make my beams and members larger in size. So, that they will be more stronger right.

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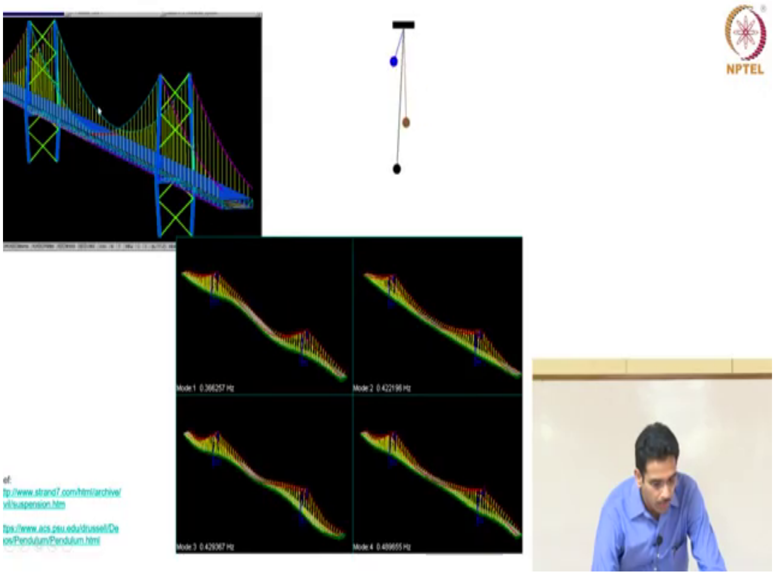

And this is another example, we just look at these three examples and then we will go into the course. So, this is another example I thought is interesting. So, this is a suspension bridge so, in a suspension bridge what you have is, you have a deck right and it is suspended from cables at the top. And suspension bridges are very important because their dynamic characteristics are very important, because when you have a bridge it is subjected to dynamic loads, vehicle loads, wind loads, earthquake loads and so on.

So, why are dynamic loads difficult to understand and why is it important to understand structures in the context of dynamic loads. So, think about a simple pendulum. Let us start with the simplest object you know, a simple pendulum oscillating. A pendulum oscillating has a natural frequency or a time period, what is that? It is a time taken for the pendulum to complete one oscillation.

And if you see I have shown here three pendulums one in blue colour other in golden colour and a blue black colour. And what is difference between them? The length of the pendulum is different that is their geometry is different. So, if the geometry of a structure in this case the simple pendulum is different, it can have a different frequency of oscillation you can see the blue one is oscillating much faster than the black one right.

Similarly, when you look at a structure depending on the size of the structure, the material you used in the structure and how the structure structural members are connected. You can have different modes of oscillation in the bottom figure; I showed 4 different modes of oscillation in a simple pendulum case you just have one mode of oscillation. So, there is just one degree of freedom is what we call it, but in a structure there are different kinds of oscillations that are possible.

For example, you can see the first figure is more like a sinusoidal curve right, but the second one is more or sort of a lateral torsional oscillation. So, different such oscillations are possible and each oscillation has it is own frequency depending on the geometry of the structure. So, in summary it is just all about how this geometry and the material property is going to affect your frequencies and how these frequencies are related to the dynamic forces acting on a system.

If you can understand that you can design the structure better for the dynamic loads.

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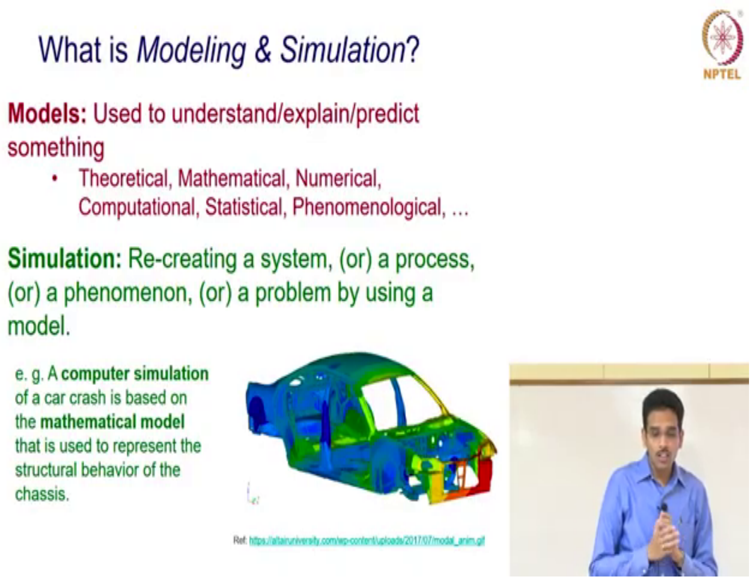

So, now let us get into what is modeling and simulation? So, what are models? This is quite a general concept as I wrote here, models are used to understand, explain or predict something. They could be theoretical models, mathematical models, numerical models, computational models, statistical phenomena phenomenological and so on.

We will see some of these in the next few slides what they actually mean and how they are different. And then what is simulation? Simulation is re-creating a system or a process or a phenomena for example, here I have an animation right. So, if this is about computer simulation of a car crash. So, if I want to understand car crash I do not necessarily have to crash the car 1000 of times in different directions, maybe I run a few 1000 simulations and then final test one or two of the of the critical ones right.

And when I want to do that what I need to understand is I want to understand a mathematical or a theoretical model for the structural chassis of the car. And then do a some computer simulation, solve this problem on a computer and then I can visualize what is happening right. So, these are some examples of modeling and simulation.

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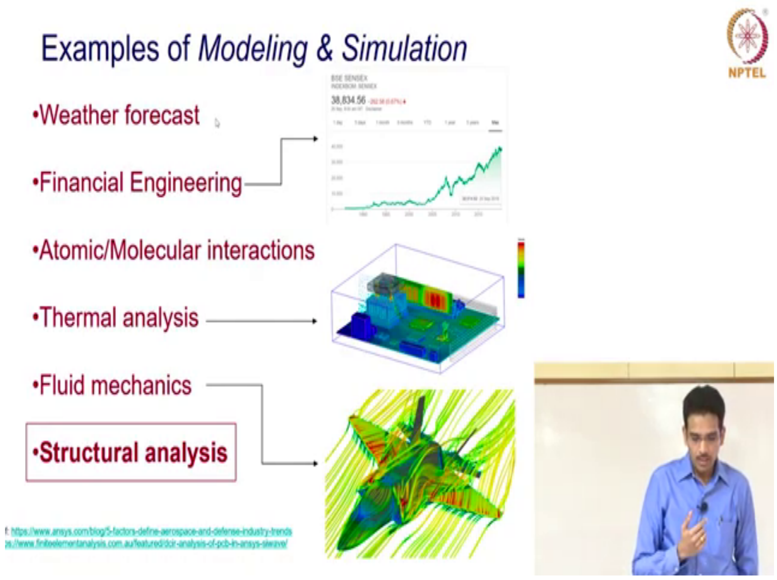

So, the first one is; weather forecast so, let us say you want to predict the path of a hurricane or when the cyclones would come, where, which states the cyclone would cross and so on.This is very important for irrigation purposes and many other water resources problems right.

So, this is typically done based on previous data and also you could maybe use atmospheric physics. So, it is a combination of physics and data problem financial engineering is related to stock markets. So, you have a stock market data based on many years the trend of the stock market. And then you want to decide whether you want to buy a stock or a seller stock depending on how you think or how you predict a stock market is going to behave in the future and for that you need a model for it. So, this is typically done using statistical modelling.

And then there are also other models for example, atomic, molecular interactions have to be modelled if you want to design drugs for some diseases right, I want to study how the molecules are going to interact form the bonds or maybe break some bonds to create new drugs maybe for cancer or some other diseases right.

So, such research can be done if you model atomic interactions using maybe some experiments as well as some physics base loss. And another example, on thermal analysis; so, this might sound a little interesting because here you are looking at a computer motherboard. So, the animation or the figure here the coloured figure here. So, is a computer motherboard and what we are trying to do is cool down a processor.

It just pretty hot in a processor in the on a computer motherboard and if it crosses a critical temperature the parts can fail even structurally. If it structurally fails you your circuits are now no longer connected and it cannot function right. So, you want to keep the temperature of the processor below a minimum level and maybe for that you want to design a fan. So, now, how do I decide what should be the shape or design of the fan what should be the speed and all that right. For that what I want to do is, I want to study how the wind passes through this processor and how does it dissipate the heat for that you want to do thermal analysis.

So, that is the modeling and simulation that can be useful in the context of thermal analysis and what about fluid mechanics? I show here a aircraft. So, in an aircrafts, you have wind flowing on the surface of the body of the aircraft and if you if you can model the wind flow on these structures you can potentially reduce a drag on the system.

So, if you are moving your hand in the wind, you can see that you have a resistance right. So, if you if I can model that wind on the surface maybe I can model the shape of my surface in an efficient way. So, the that drag will be lesser if you move it like this versus like this there is a difference right so, that is what you are trying to understand. So, that is related to fluid mechanics because air is a fluid.

And then finally, we look at structural analysis which is a main theme of this lecture right, we look at the overall context of modeling and simulation in the context of structural analysis.

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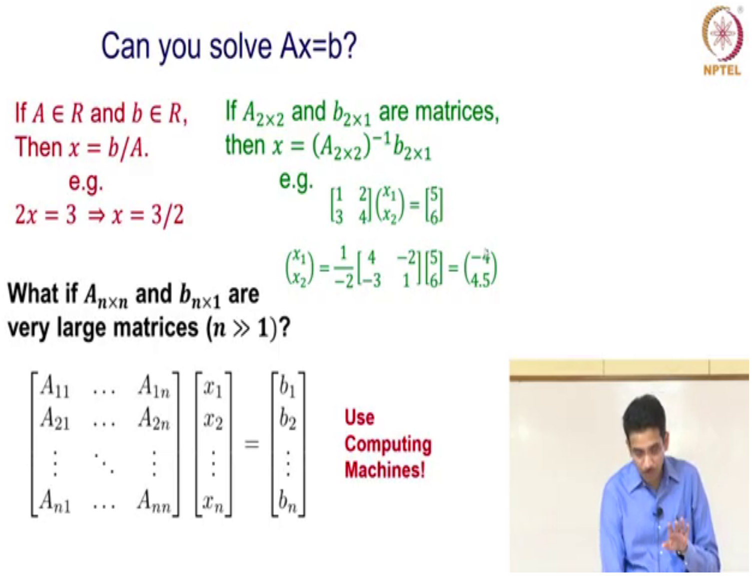

So, before we go into the actual talk let us motivate ourselves, why computers are important? I am sure you know you know why computers are important for various reasons, but in the context of modeling and simulation, why are they important?

Let us start with the basic problem one of the basic problem, so, can you solve A x equal to b right? So, what do you need to solve A x equal to b an algebraic equation? You need a the input A and b and then if A is a real number and b is another real number you should be able to tell me, what x is. For example, if 2 x equal to 3 x is just 3 by 2 right. Now, what if I say A and b are not just single numbers, but they are matrices right.

So, if A is a 2 by 2 matrix and b is another 2 by 2 matrix such as the one shown in this example, can you find me a vector of size 2 by 1 from this given input, which is quite trivial you just have to invert this matrix which can be trivially inverted for a 2 by 2 matrix as shown here and then multiply with the right side vector you get your unknown x 1 and x 2. But then if I ask you can you solve this matrix system with an n by n matrix and an n by 1 vector on the right hand side?

So, you are basically I am asking you to find x 1, x 2, x n where, n could be may be 1000 I am asking you to solve 1000 equations at the same time can you do that manually? No right. So, why do not we use computers for that? So, let me put this into a bigger context.

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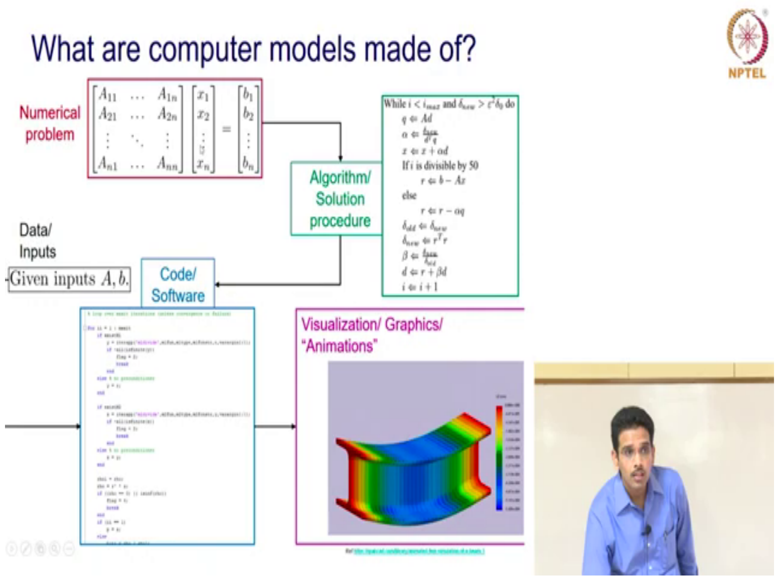

So, what are computer models made of right? So, I have this numerical problem in terms of a huge matrix and a set of unknowns x 1, x 2, x 3, x n and then given b 1, b 2, b n right. So, let me give you a physical context of what these means.

At the right bottom corner on the screen, you are looking at a beam which is undergoing some sort of animation I will explain, what is happening. So, imagine this b 1, b 2, b 3, b n each element in that vector, corresponds to a vertically downward force at each point on the beam along the length of the beam. So, let us say I am applying a b 1 here, b 2, here b 3 here and so on b n right.

Now, correspondingly if I am pressing a vertical force on the beam, there should be a displacement at those corresponding points. Now, I will denote x 1 x 2 x 3 x n as a corresponding displacements at all those forces. So, now, if I solve this matrix problem A times x equal to b for a given set of forces on the beams, I can find the given set of I can find the corresponding displacements on the beam.

So, that is the structural analysis problem. Now, once I establish the context of this problem, I have this numerical problem; which I have to solve, I have a matrix, I have a force set. And I want to find the displacement on the structure how do I solve this matrix problem right it is a linear algebra problem you typically have algorithms or solution procedures for standard problems in terms of the properties of the matrix A.

So, for example, you might have a heard about gauss elimination method right on how to solve a matrix with a lot of unknowns and so on right. So, you can use such an algorithm or you can use different algorithms such are all shown here and that should be able to solve the problem so that, is all theoretical you have a mathematical framework or how a how to solve A x equal to b?

Now, how do I use a computer to solve a problem? Because even if I have an algorithm, if I have to solve a 1000 by 1000 problem I cannot do it manually right. So, I need to tell a computer of how to understand this mathematical algorithm and solve it for that, you need to use what are called programming languages like; C or Python or FORTRAN or MATLAB or whatever you are comfortable with.

And then, translate this algorithm which is shown in this green box into a code or a software. So, once I have my software all I need to do is give the inputs to the software which is all the elements of the matrix A and all the elements of matrix b and then this software using this algorithm should be able to solve for all the vector x i right. So, once I do that, I can visualize my results using graphics which is shown in the last one.

So, what is happening here is actually, I started with a set of forces b 1 b 2 b n and I kept increasing the magnitude of the forces; I kept making the forces larger and larger and at each point I am trying to find my displacement x 1 x 2 x n. So, as you can see as the forces are increasing the displacement is also increasing right for each of those I am solving that matrix problem.

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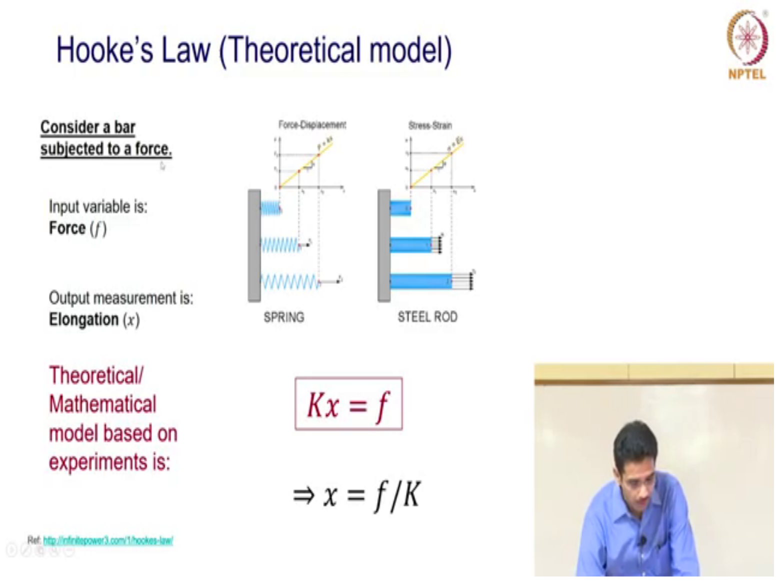

So, now, let us see how one could develop a theoretical or a numerical model for a typical structural engineering problem right. So, you are all familiar with Hooke's law right if you have a spring and if I apply a force on it, the displacement of the spring is or the elongation of the spring is proportional to the applied force and this is the standard basic Hooke's law.

And it is given by this expression K x equal to f. So, in this case f is the input variable force on a spring and x is the corresponding elongation. So, this is also shown in a plot here. So, the x axis corresponds to the displacement of the spring, y axis corresponds to the force. And let us say you take a real spring and start applying forces maybe 10 Newton's, 20 Newton's, 30 Newton's and so on. For each force you have a displacement.

So, once I have that I will mark the corresponding displacements and I will make a plot as shown here. Once I join all the lines. Firstly, I will notice that there falling on a line and once I join the dots I get a slope of the line and that slope is nothing but the stiffness of the string given by K.

Similar analogy can also be applied for a steel rod. Steel rod is also a spring, except that the stiffness of it is much higher than a normal spring you see right. So, again you have a Hook's law for a steel rod and why is this useful? Now, once I have a model. So, let us call this the theoretical or the mathematical model for a spring or a rod, there had based on experiment.

Once I have this model next time you give me a force applied on the spring or the rod, I do not have to go back and do my experiment right. The model is now able to predict the displacement that can occur in the rod so that is the idea behind developing a theoretical model and this is very simple and it is kind of obvious if you can think about it right.

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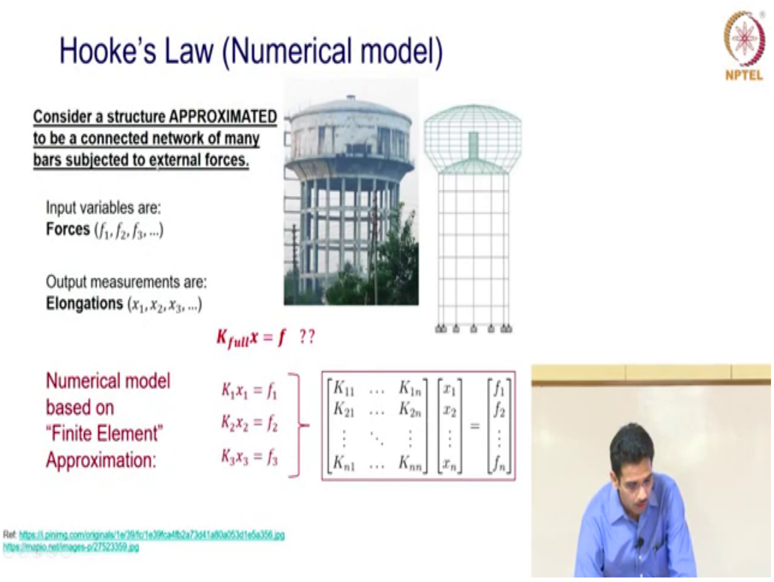

But now let us go into slightly complex problem. So, let us say I have this water tank structure shown here right. And then I am saying I want a model for this structure, because in the end all I am interested in is I want to apply forces on my structure at different points. Let us say f 1 f 2 f 3 are various forces applied at different points on my structure right.

And for those corresponding forces, I want to find the corresponding displacements; because those forces will cause some displacements or distortion of the structure that is what I want to do. What do I go back what do I do based on my previous experience? I how to do an experiment.

So, if I can do an experiment with forces and displacement and make a plot and maybe potentially find is K full the stiffness of the structure then I am good right, but how easy is it to perform experiments on structures like this or maybe more complicated structures which we will see eventually right. It is not quite feasible, at this point we use the math and develop what is called numerical models.

Since I know how to deal with a single rod I can approximate this entire structure as a combination or a network of many bars which are subjected to courses. So, each bar here is connected to every other bar and it is kind of approximates this real structure. So, when you are approximating you know you are dealing with a model now this is a numerical model right. And since I know for each bar I can write K 1 x 1 equal to f 1 because each bar still obeys the theoretical Hooke's law which we saw in the previous slide.

And for the entire structure all I have to do is combine all the equations from the bars and develop this huge matrix right. So, this huge matrix and displacements at each of the rods and the forces on each of the rods is what dictates the structural behaviour of my complicated structure.

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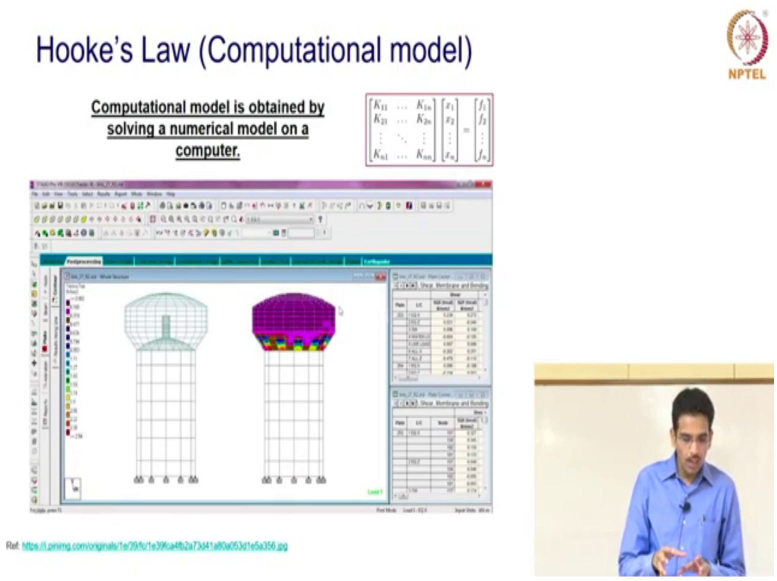

So, this what is what represents a numerical model for this problem. And once you solve this numerical problem on a computer because it is. So, huge and you cannot solve it manually that becomes a computational model.

So, you take a real structure you convert it into a numerical model and then you solve the problem that is; when you press some buttons here, but what is actually happening once you press the buttons these are the code is running and it is trying to solve the matrix problem that is giving you the displacements or forces or whatever you asked it for. And then you can visualize the results and see and make sense whether your structure is safe or are you with it do you want to change it and so on right.

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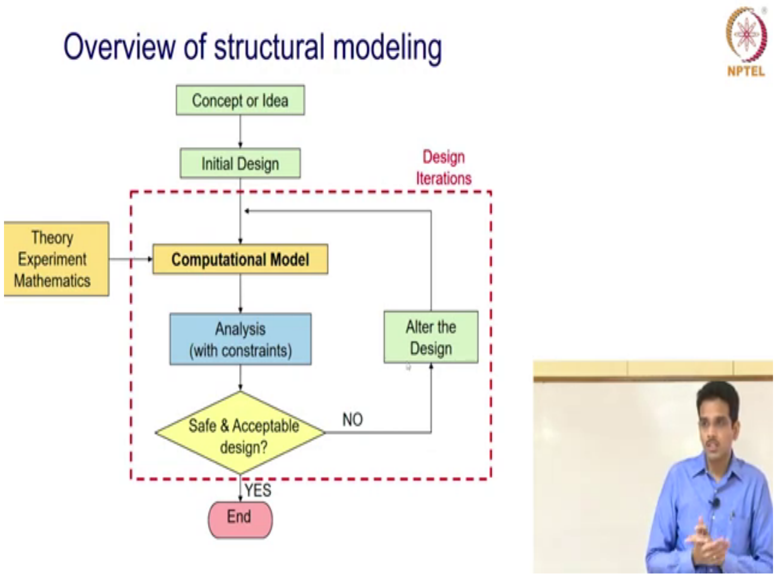

So, let us put it put it in the overall context of what you might have seen in the previous two classes on structural engineering, maybe you heard about analysis and design and so on right. So, what is happening? When somebody wants to build a structure or a bridge or something they start with an idea yes, I want to build a bridge here or I want to build a building in this location. And this location is characterized by such and such atmospheric forces or temperature and so on.

Then this is the material requirement these are available in this location these are not and so on right. Based on all that you start with an initial design or a preliminary design for your structure right and once you have your design based on what we just saw you would you can you cannot do a full scale experiment for it, in some very rare cases although that is possible but, let us in general it is not possible.

So, you construct a computational model for the initial design and this computational model is informed from theory, experiment as well as mathematics right. So, once you have a computational model, you run it through a computer and perform the analysis and see whether the structure is safe and acceptable whether, that design you came up initially is it safe and acceptable, can it take all the forces without failing in the structure stand or will it fall, if it is safe and acceptable. You end your design and you are you can you are good to go with your initial design.

If not you go back maybe change this layout of your members or you change the sizes of the members to make it stronger or less strong or whatever you want. And then go back and update your computational model again because, now you change your structure and then perform the analysis. And this loop keeps going on until you are satisfied with it. These are what are called design iterations. Typically if you are performing any structural analysis or building a new structure many 100s of such designs are possible depending on the complexity of the structure.

Now, imagine if you do not have this computational modeling capability or structural modeling capability, you would have to perform experiment for each structure you come up every time you change and you think this is not good enough for me you have to perform an experiment because you do not know the stiffness or property of the structure right. So, this analysis actually is cutting down, the time on your design iterations and helping you have design the structures more efficiently.

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So, now let us look at some applications on how the structural modeling has helped in designing some of the most complicated and wonderful structures on this planet right. So, this I am sure you might have seen in other lectures in this course Burj Khalifa one of the is the tallest building on the planet right. And there are some interesting aspects to it from the context of structural modeling and simulation.

So. Firstly, when I say you have a very tall building, extremely tall building, what is that? That comes to your mind imagine, you are on the top floor of the building high wind loads right, there is going to be very high wind loads. So, how is this building different from any of the other building because you are at such high level maybe you have a stream of jet winds coming onto your building and that might affect some structural dynamic behaviour which we have discussed in the beginning right.

So, what typically happens is, if you look at this blue part of the animation I am showing you a cylindrical structure which is put in a fluid motion. So, the fluid let it be wind or water it is moving on the cylinder and once the velocity of the fluid crosses a particular point you will see what is called vortex shedding, which is happening here. So, there are some kind of features in the fluid that keeps moving out away from the structure.

And if it is happening at some frequency, that can resonate with the structure and make your structure oscillate and that can be very bad for your structure. It can even lead to collapse of the structure. So, you do not want your structure to be a cylinder and standing so tall and your wind is so bad, that you have vortex induced vibrations, what they are called. So, you have to overcome the designers have come up, with this interesting design where they have cylinder staggered as you go up if you see this structure there is some sense of spiral action going on here.

So, the cylinder height is here and here it is higher than that, here it is higher than that, higher than that and so on. So, this staggered pattern disrupts this kind of periodic shedding that is happening on the structure right it prevent vortex induced vibrations and if you see the final wind simulation of the building you can see there is no such periodic shedding happening it is all dissipated here and that is how you know this building is not going to fail under such wind induced loads.

And all this is possible if you could do just simulate it right it does not cost much, but imagine you would have to make a real experiment of such a large scale structure it is not possible. There are some extreme cases like; I said before maybe you can make a scaled a model of the structure and then test it in wind tunnels, but even that is pretty expensive, but compared to making a computational model and studying which wind loads are the most critical is much easier right.

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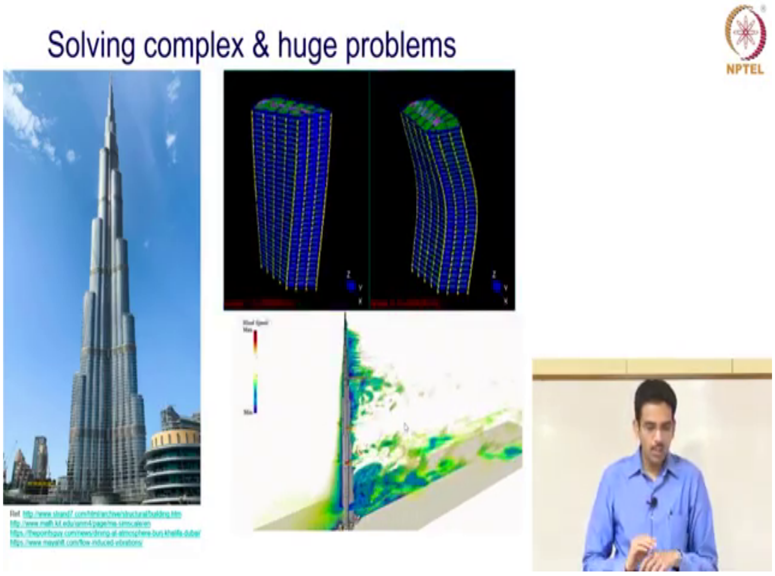

And this is another example where you have an earthquake load in the building. So, it is oscillating in different modes. So, you want to study again which dynamic modes are critical for the building and so on.

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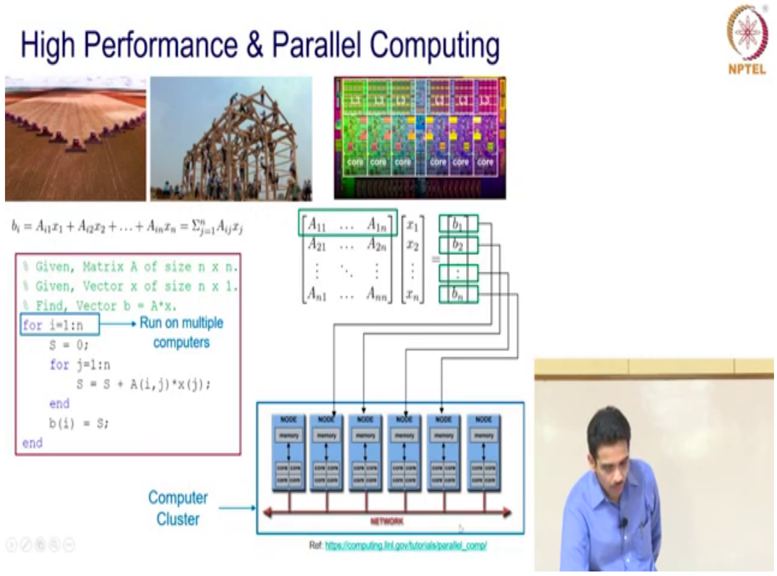

Now, if you see those buildings and if you count the number of rods, we said we will described the structure wave you can imagine your matrix size could be running into 1000s right; in some of the cases it will be of the size million by million or hundred 1000 by 100 it will be in the orders of millions in many of the structures when you have very small rods it is for approximating in such a huge structure.

So, can your computers actually solve that problem of million by million matrix times, some vector is given forces. A simple standard computer cannot necessarily solve very huge problems, in such cases you have to deal with what are called super computers. So, for that what you need to understand is this high performance and parallel company. And I thought it is very important that you know about this at least a little bit background on this, because in today’s world most of the computers even the personal computers you are using are using parallel computing.

Parallel computing need not necessarily mean you have ten computers in front of you. All you are doing is your many course and whatever job you are giving out. So, let us say how to make some calculation I do not want to make the calculation one after another I want to do them all parallelly. So, let us see how that works? So, let us say I am interested in a matrix times a vector. So, I want to calculate this matrix time’s vector. So, how do I typically calculate? I calculate b 1 as product of this row times is vector right. So, A 1 x 1 A 1 2 x 2 and so on A 1 n x n.

Only after that, I can go to b 2 and do this row times this and so on. So, if I have to write a MATLAB code for this, you have it here. So, for I equal to 1 2 n that is; for each b 1 or b i calculate the product of the row elements of the matrix A i j times the corresponding elements of the vector x i x j and the way this thing works is first it will calculate b 1 then it will calculate b 2 and so on. So, what we suggest to do is, you run it on multiple computers the first loop. So, what I want to do is I want to calculate b 1 b 2 b 3 b n all simultaneously. And just to get an intuitive understanding of what is happening here, I have a couple of figures taken from the large form of website.

So, in the first figure you are looking at flowing a field you have one tractor or one machine you want to flow a field versus 100 tractors going at the same time, you can finish the whole field in the time taken by one tractor to travels the field right. An another case you are constructing a building 1 worker versus 100 worker workers working on it at the same time.

So, that is the idea. So, now, what we want to do is, I will calculate my b 1 in 1 computer or one node or one CPU and b 2 in another CPU b 3 in another CPU and so on. But, what we need in extra to what we already have with l standard computers is we need a network which connects all these computers.

To tell me that these b 1 b 2 b 3 it belong to the same problem that is called a computer cluster And there are many thousands of computers that can be connected and very huge problems can be solved on them parallelly.

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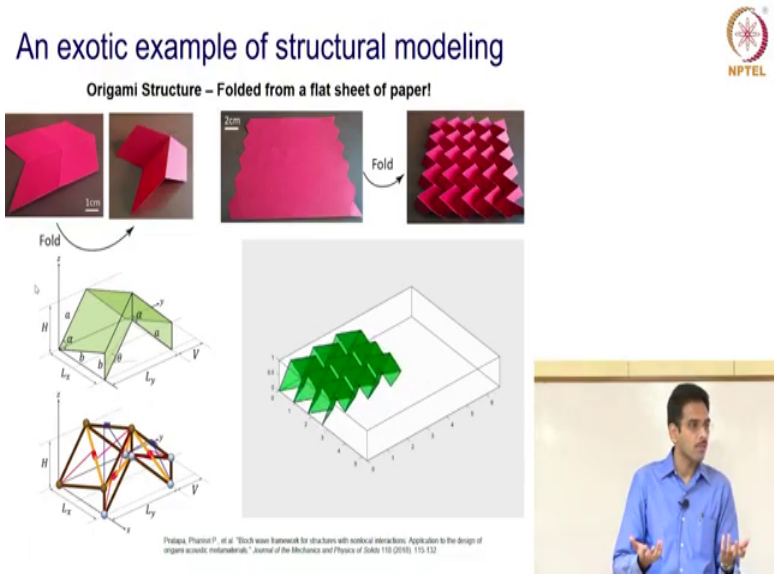

And let us look at an exotic example of structural modeling. I thought this is this is interesting because it would give you a sense of how can I come up with a structural model for a structure which I have not seen before. For example, I have not seen this structure before this is a folded structure made out of a flat sheet of paper and it turns out it has some very interesting properties.

So, you see there is a flat sheet of paper and somehow I folded along it some corrugation and you end up with the structure right and each part of this cell is again shown here in detail just for you to get a understanding of how it looks. And let us say I want to model it structurally.

So, before I go into structure model I want to show I have a paper model here you can come and see it after the class. So, it has an interesting behaviour if I pull it out it extends in both the directions, why is this interesting? You take a rubber sheet and pull it out, it contracts in the other direction, but in this case if I pull it out in one direction it is extending in the other direction right.

So, this is called a Miura origami sheet, origami is art of folding paper. So, now, let us say I want to do a structural model for this. So, I take my unit cell, I understand it is geometry in terms of something shown here, but now structurally I want to model it, what do I do? I go back to my idea of replacing the structure with bars right and bars are nothing, but springs. So, I have a quadrilateral panel here.

Firstly, I replace my quadrilateral panel with a set of 4 bars then I understand that the opposite corners of the quadrilateral panel cannot be independent they cannot just go out as they want, because it is just a plate right. So, they have to be quite rigid; that means, I have to put another bar connecting the diagonal that is a more realistic representation of this panel right so that is how I come up with a model and I put some spin springs on it to give a structural behaviour and after I do that I model it on the computer right,.

I simulate it on the computer. And you can see it can give the same behaviour as I have shown you as you pull it out in one direction the other direction expands and if you contract in one direction the other direction contracts right.

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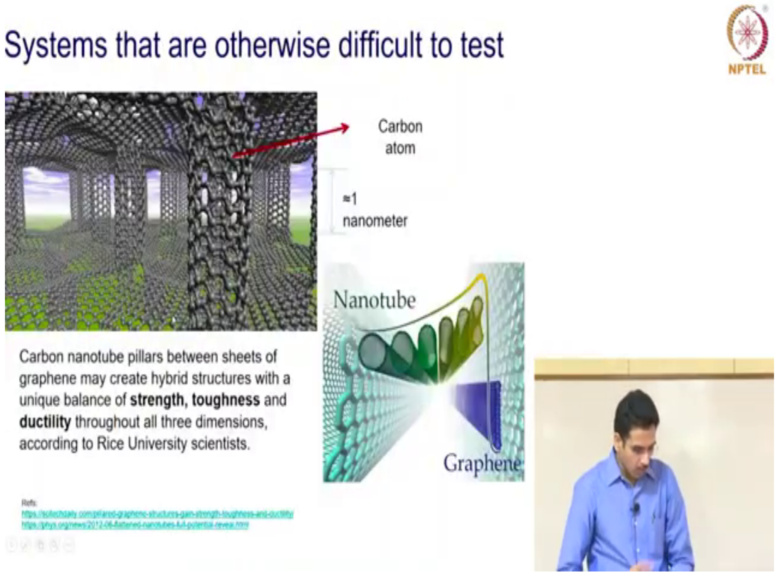

So, this is how structural modelling, can help you understand structures which you did not know how they would behave for example, and there are also other systems such as atomics systems such as one shown here. So, this is a combination of graphene and carbon nanotubes these days you might be hearing a lot of these buzz words, carbon nanotubes, graphene and so on.

They have interesting properties electronic properties and so on right, but even structural engineering has a role to play over there why is that, in the in the end nobody wants things to fail structurally by making an electronic circuit or a P C B or whatever I do not want it to break I wanted to be strong enough for whatever stresses even if that is undergoing.

Even the smallest things are subjected to forces I do not want them to break right. So, in this case researchers have found that if you combine carbon nanotubes which are shown as pillars here. So, these are carbon atoms and then if you combine the graphene sheets they have a better structural property than both of them working independently and this has lot of applications in electronics. And a structural engineers I see there see them as columns and slabs and beams and it is the same concept right. In fact, the researchers who found this idea was civil were civil engineers from Rice University.

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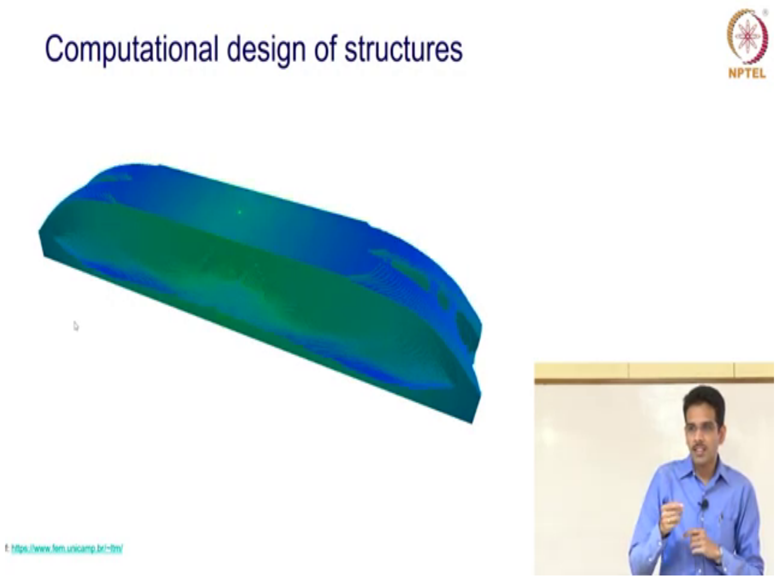

So, this is another interesting application of modeling in the previous flow chart where we discussed design iterations.

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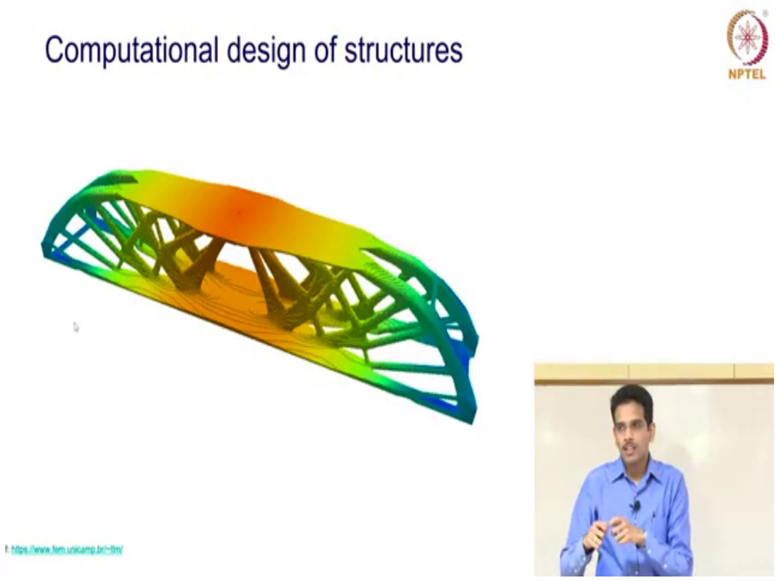

I said once you are not happy with your design you go back change your member sizes and analyse it again. But does not it seem a little bit inefficient that I have to tell the structure what to change, what to increase, what to reduce and so on right. It would be nice if I have some sort of model maybe an optimization model which tells the structure no now you want to remove the material there or maybe increase the material here to make it more efficient so that is; what is happening here.

So, I start with a cuboidal domain shown in blue colour, initially and then I applied a load at the top and then I gave it a modeling algorithm which says remove the material which is or inefficient which is not taking load efficiently and that is going to give you the beam structure which uses the least amount of material.

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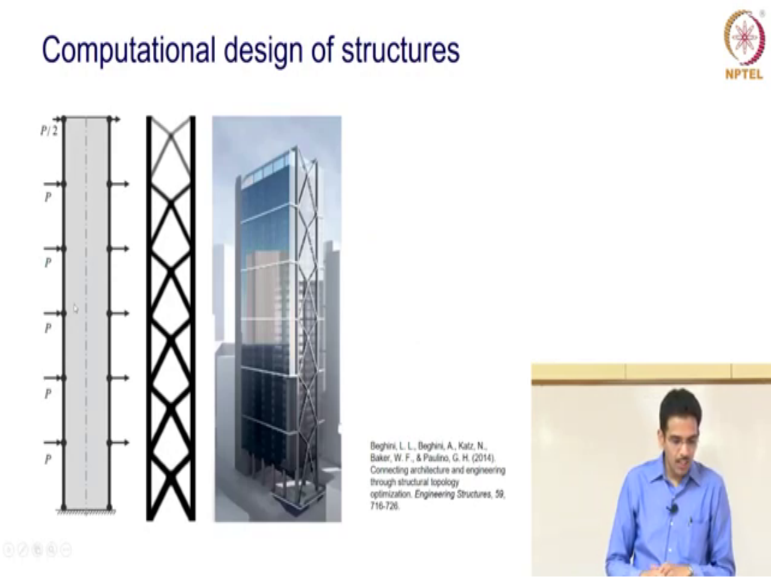

And if you can use such algorithms to design futuristic buildings such as the one shown here you can get these kind of bracings which are similar to what you might have seen in standard buildings, but are also slightly different. And there these are supposed to be at least theoretically optimally optimal and more efficient in terms of structural efficiency.

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And if we have time we can go or and in detail on what kind of cantilever structures you can obtain using this algorithm. I think you might have seen the cantilever structures in your previous lectures cantilever is you have support on one end and I apply a load somewhere else. And in between that I want to create a structure which can take this load to the support right.

So, that is explained in this figure here and these are some examples of cantilever structures, where you have the support on one end and you have a huge structure in between.

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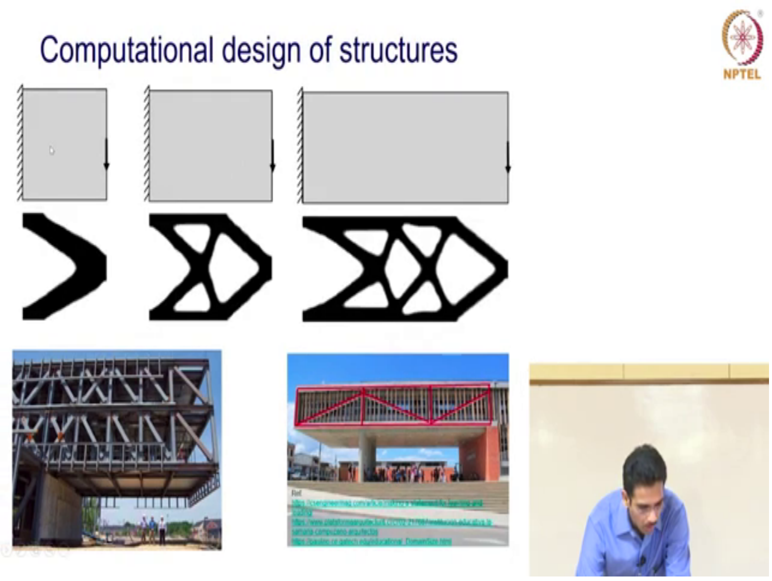

So, let us see how they are compared to what this optimization algorithm would give. So, the optimization has told me that with this length is small enough I just need v type brace and as you increase the thing you read more and more braces to transfer this load to the support right.

But one thing is common between what is existing and what are these braces are common, but the way the braces loop and the amount of bracing that has to go at one end versus the other end that is changing right. So, of course, there is hope that you can make structures more efficient maybe you can use 50 percent of the material that was used in this to get the same structure and be more efficient right.

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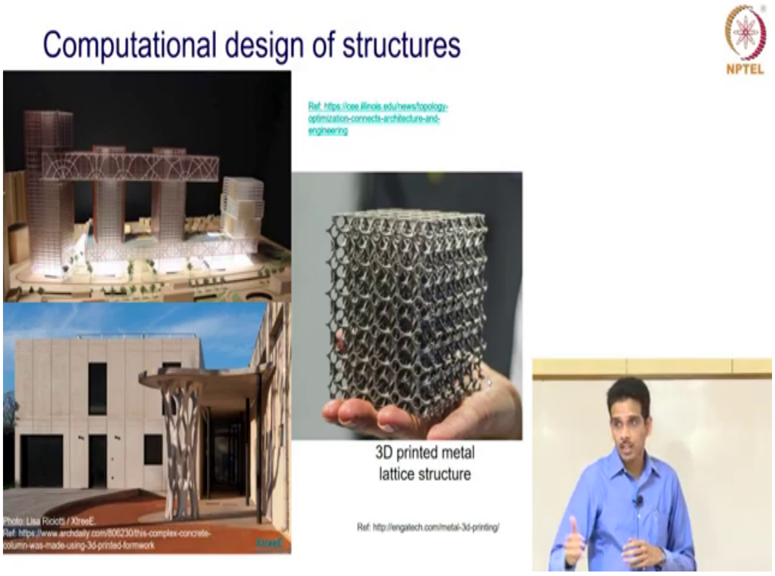

So, all is sounds good and it looks interesting, but can we actually build it right that is call in the question you have in mind. So, here is an example of concrete structure this column is made out of concrete and typically you might not have seen concrete in some random forms, but even if you have to build a concrete in some weird shells shape and so on. You have to take a lot of effort to make the formwork for the concrete and so on.

In this case they have used 3D printed form work to make this complex 3D structure. So, what I would like to highlight here is it is not impossible to make structures which were not possible before there are always advances happening in the field to build structures using innovative techniques and what you thought might not be possible might be a reality tomorrow right.

And another surprising thing is you even have 3D printed metal lattice structures and these are right. Now, actually being used in the industry so, industry is actually 3D printing metal lattices to be used in automotives or manufacturing and so on. So, that is already that already has become practical.

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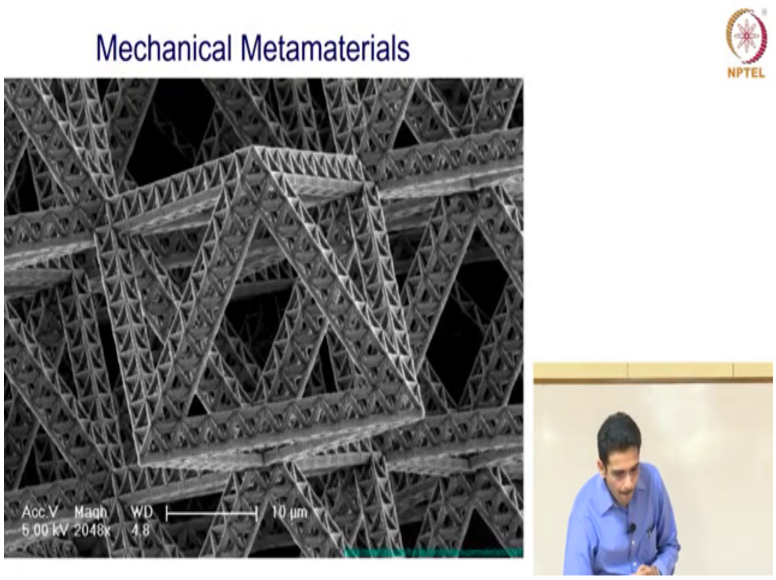

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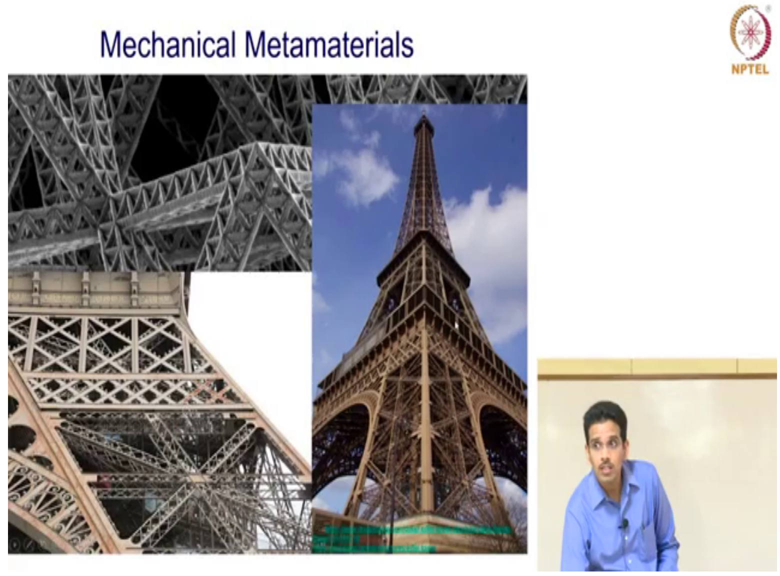

Can anybody guess what this is? So, does it look something like a part of an Eiffel Tower right, maybe it would like this truss structure right, but if you notice this length scale I showed here, it is telling you that the length measurement from here to here is 10 micrometres, what does it mean? The entire width of the slide is about the thickness of your hair strand.

So, somebody actually sat down and use some advanced manufacturing techniques maybe such as 3D printing to build a structure within the thickness of your hair strand. And that structure is inspired by the big scale structures like a Eiffel Tower. And why is this important, how does this make sense or who cares about this right? So, if you think about it when I was tell talking about optimization algorithm I was talking about removing the material which is not taking the load and making the structure more efficient if I am using less material I am causing less environmental impact in some sense.

So, that is one of the motivations you want to design your structures in a more efficient way right. So, if you are removing material which is not being used you are making a structure light in weight and also having the same strength. So, you are making your structures light weight and high strength. So, many of the structures you see around maybe they have too much weight just because we do not have any other way to manufacture them. So, you do not want to do that right. So, these are called mechanical Meta materials they are made in some exotic ways and they are some exotic properties which you might have thought are not possible.

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So, another example on mechanical metamaterials so, what are metamaterials? Just definition here is, their artificial materials that can exhibit exotic engineering properties, what is exotic? Something fancy, something you thought it is it does not make sense to me maybe something like that. So, let us look at this example, inner visibility clock maybe most of you know about

Harry Potter's invisibility clock right. So, it is a garment then you enclose it around an object, you will not be able to see the object does it physically make sense the is it just pseudo science or science fiction or something or does it make sense physically. It can be explained physically, but the practicality is a different question.

So, let me try to explain what is actually happening when we talk about invisibility clocks. So, on one end the light waves are coming in and there is an obstruction and somebody is viewing the light waves from here right. If there is an obstruction I should not be able to see what is there behind it that is a reality. Now, if I can make some kind of meta material around this, which will behave in such a way that it will take these waves it will manipulate then in such a way and send out the same waves as they are coming in such as a one shown on your right side.

If I can do that, somebody is sitting here they will exactly see these light waves as they are here which means they will not see what is there here at the black dot they will not be able to see that is a idea of invisibility clock and meta materials has read with it. So, practically, we still do not have it yet, but I take inspiration from this towards what are called elastic or acoustic metamaterials instead of light waves.

Let us say you have sound waves are maybe structural vibrations, I can use the same idea to create some sort of meta material around some structure I want to protect and make sure maybe these waves do not touch my structure and just go away right.

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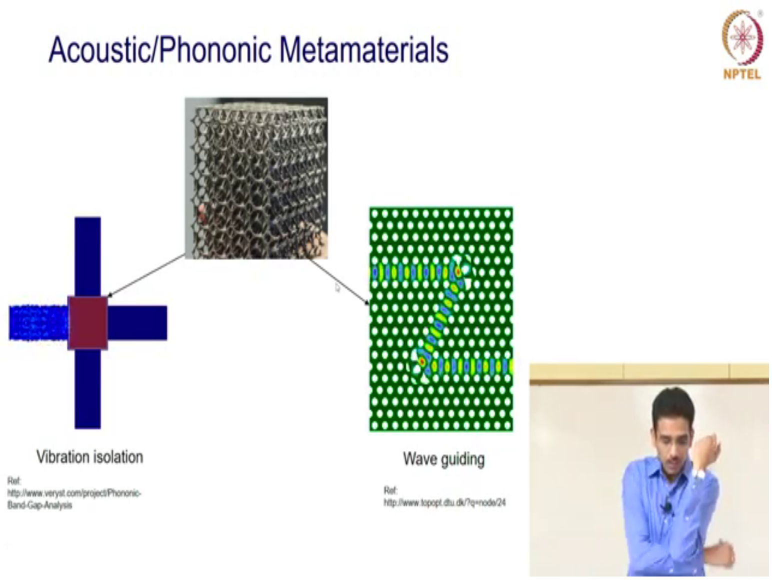

So, that is explained in this simulation here. So, let us say I have some meta material so or in some saw some sort of this lattice shown here, and then you have some vibrations on one structure. And I do not want this vibration to go to the rest of the structure. Now, if I can design this geometry of this structure using some optimization in such a way that these vibrations cannot pass through this that is they will be repelled or absorbed by this lattice then I can pre protect this part of the structure. So, you can you can isolate the vibrations.

So, another example is wave guiding. So, I have this lattice and then you can maybe distort the lattice in some way to make the waves propagate in some particular direction you want right. So, the theoretically this is all possible, there are challenges there are limitations, but the good thing is now theoretically it is not it does not seem nonsensical. So, let us say I have sensitive structure may be a nuclear reactor and I can put such a lattice grid below the ground.

And then if I can maybe play around with my lattice and design my geometry of the lattice you can potentially control the vibrations, maybe the earthquake vibrations coming to the structure, go around the nuclear structure and make it safe right. So, the modeling and simulation the importance of the context here is you still do not have these systems you do not have any experiments, but the theory and the models that have been developed fundamentally can be extended to more complex ideas which can result in futuristic structures and materials that is what I want you to take away from this.

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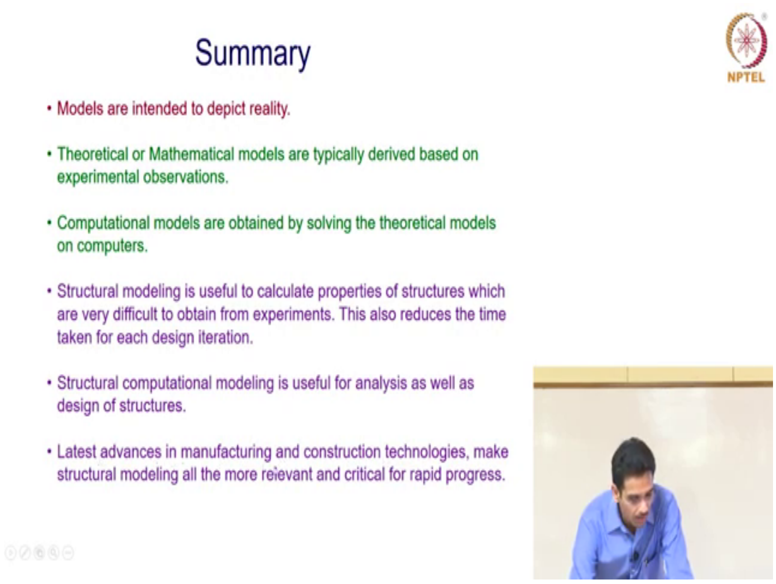

And now, let us summarize. So, I will just go or briefly on what the major topics which we which we have touched upon. So, the first thing is; models are intended to depict reality models are not reality we want them to depict the reality as best as we can using experiments or other insights. And theoretical and mathematical models are typically delivered based on experimental observations in most of the cases.

But also there are cases where you can derive from first principles or fundamental laws for example, maybe Newton's law of gravitation or maybe quantum mechanics can be used to understand atomic interactions using fundamental laws, not necessarily entirely based on experiments. And computational models are obtained by solving theoretical models on computers, which we have seen and we have seen the importance of parallel computing in solving large scale structures. And structural modeling is useful to calculate properties of structures, which are very difficult to obtain from experiments and this is what we have highlighted in this lecture.

And we also noted that it reduces the time taken for each design iterations; it does it makes a designing process of the structures more efficient and structural computational modeling is useful for analysis as well as design and this is a novel concept relatively in a sense that the optimization frameworks that can also design the structures are not very rigorously or widely used in the industry yet.

So, there is a transitioning phase that is coming in, where now you can design and analysis do everything with modeling. At least that can give you an insight on what the best designs can be and then of course, you can have a human factor in to make it more practical. Finally, latest advances in manufacturing and construction technologies make structural modeling all the more relevant and critical for rapid technological progress.

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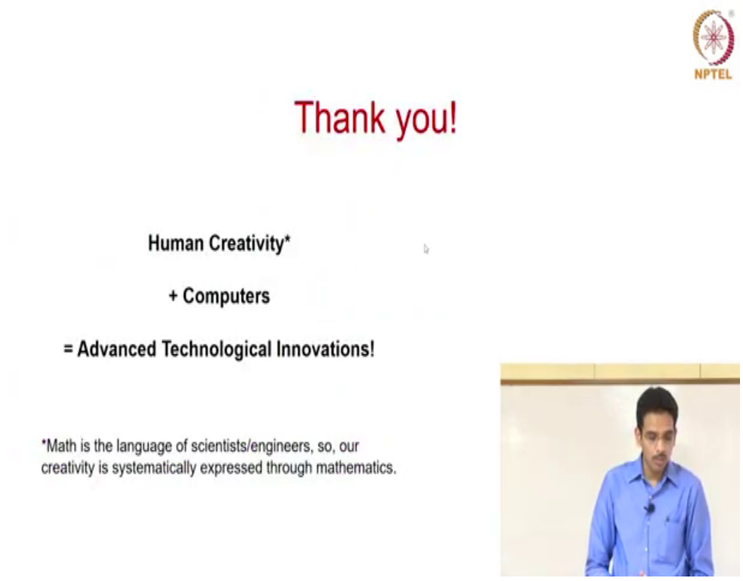

Finally, I would like to conclude this slide. And I believe that human creativity plus computers make advanced technological innovations feasible.

Thank you.