Introduction to Finite Element Method

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Lecture - 1

In this course we are going to look at the computational methods in design and manufacturing. As you can see the word computational methods indicates that we are going to look at the way in which problems in design and manufacture will be solved using numerical as well as computer methods. About 40 to 50 years back people were solving complex problems or at least trying to solve complex problem using what are called as analytical methods. But as the material development took place, as the complexity, both geometry as well as shape of the components, became quite complex, people were not able to use the analytical methods and they started using numerical methods. We will go into the details of the numerical methods in this course. The three most popular numerical methods being what is called as final difference method, finite element method and what is called as the boundary element methods.

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Of these three methods, today finite element method is extremely popular and in this course we are going to concentrate on finite element method. In fact, if you look at the number of softwares that are available today on finite element method you would see or at least you would hear about numbers ranging from about 400 to 500. In other words, if you include all the commercial softwares and softwares that are available in universities you would count even up to 500; it is a phenomenal number. In other words, it has just exploded over the past 10 years. If you look at very popular commercial softwares then at least there are about 10 to 15 of them which are used in the industry and in the educational institutions and research institutions.

There are number of reasons why this has happened. One of the major reasons is that the industry is today tuned to the fact that finite element methods can be used to solve lot of practical problems. That has given an impetus for this kind of explosion in the market place of finite element method. The other reason, more important reason is that computers have become now very powerful and are affordable. Lot of companies today can buy high end workstations to solve very complex finite element problems which will be very useful for them to develop their product. That is the second and more important reason why finite element method has become very useful.

Though finite element method started about 40 years back, 1950's rather 56-57 and Boeing Aircraft Company really launched a project to determine the stresses in their air craft wings, the method actually took off in the 70's; late 70's, early 80's. Initially up to about 60's or 60-61, there were about 15 papers that were published in this field of finite elemental method. Today we have about more than 20 to 25000 papers that have been published. That shows the explosion in the research front as well. Very complex problems can be solved using finite element method. Both the theory as well as the implementation has developed considerably over the past 10 years. The method as such is not very difficult to understand but the theory is more difficult. In other words the crux of the whole issue is very simple; it can be explained in a matter of 10 minutes and the whole philosophy of finite element method rests on what is called as the divide and conquer.

Now let us look at a simple problem and let us see how we can do this problem. Let us say that I have a sheet. My whole idea is to find out what is the area of this sheet?

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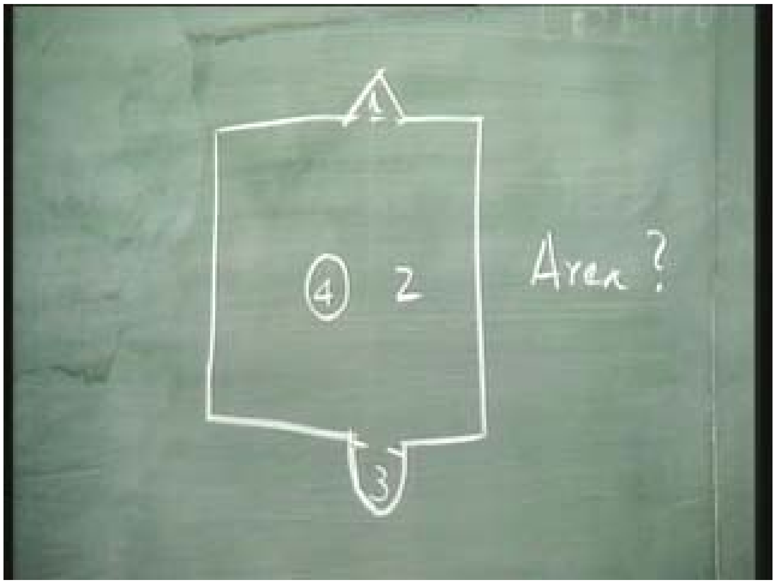

What is the area of this sheet? How do you think you can do this problem? How do you think you can do this problem, the area of a very complex sheet? Exactly. We divide this into known geometrical shapes. For example I can say that I will divide this into 1, 2, 3 and 4. In other words this property called area for some standard shapes are already known to you. In fact the calculus behind it did not come to your mind that I have to integrate and so on. But what came to your mind is that there is a relationship between this shape and formula which I know already. For example you know the formula for a square or a rectangle, a triangle and semicircle and so on. So, the first thing is divide the given area into a number of smaller geometrical pieces.

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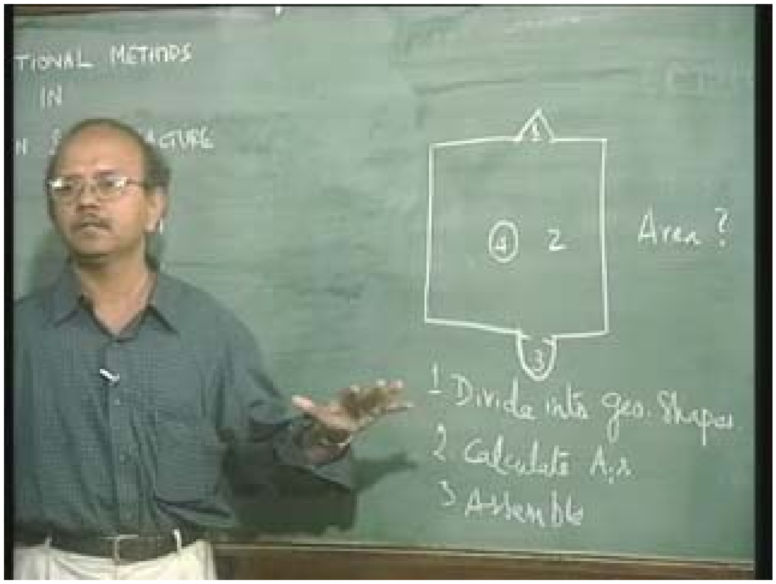

What is the second step? The second step is to calculate the area of these individual geometric pieces. The first one is divide into geometrical shapes which automatically means that into shapes whose area you know. The second step is to calculate the individual areas of the shapes. Let me call this as A_i's, where A_1, A_2, A_3, A_4 indicates the areas of this individual geometric pieces. What is the third step, what is the third step? Assemble them; it is not add, but assemble. Why do I use the word assemble? Because 1, 2 and 3 can be added and fourth is a hole and so it has to be subtracted. So, the third step is to assemble these areas. Once I do this or do the addition I get the complete area of this particular complex sheet.

The problem of finite element method is very simple. If I wanted to calculate the complete area in one go it would have been difficult for me. I am not saying it is impossible, it would have been difficult for me. There are number of ways in which I would have done the same problem. I could have divided this into many more number of squares by putting some sort of grids here and approximating the grids such that I ultimately cover the entire area. That is one technique but another technique is what we did here. Another technique, more difficult technique as I said, is to use more theorems of calculus and calculate independent or the total areas.

The finite element method relies on techniques or the concepts which we used here. It is not of course used to calculate areas, but things like displacements, temperatures, velocities, stresses and so on. What we will do is before we even go through what finite element means we will look at a few problems in order to understand its application areas or in other words let us now understand why we are going to study this course? Once we know that, it would be possible to appreciate the importance of finite element analysis as well as understand the things that we should learn in this course in order to apply whatever you have learnt here in the practical as well as in the research fronts.

I know there are lot of research students also here. What I am going to do is to give you a few examples now, go back to the theory of finite elements, explain the theory of finite element analysis, come back to these examples and show you why we have done these problems in this fashion; then go back to the theory and expand the theory in such a fashion that it would be possible for you to attack many of the complex industrial problems as well as research problems.

I am going to now summarize some of the work that we have done over the past 2 to 3 years and these projects have been sponsored by different companies. You can also read the companies that have sponsored these projects which clearly show the practical significance of this technique. Let us look at the first problem and let us now see what we have exactly done with this problem.

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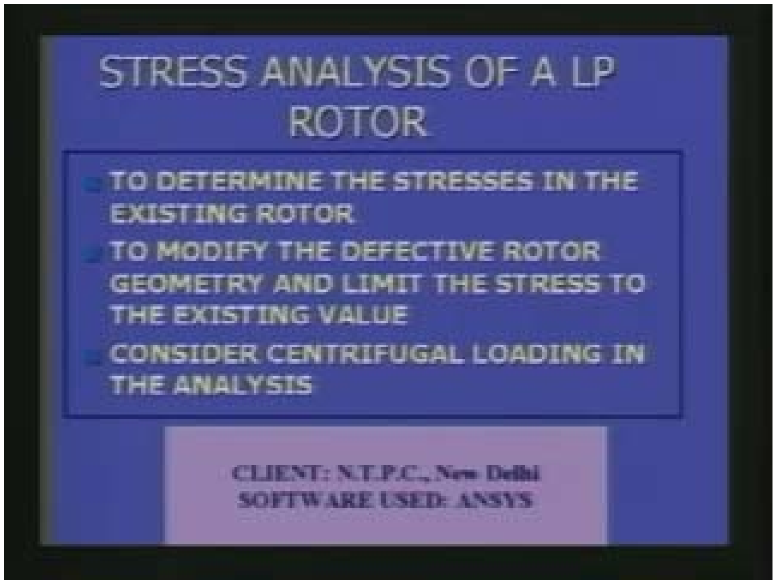

The first problem is the stress analysis of a LP rotor, low pressure side rotor done for NTPC, New Delhi. You can see that our major aim is to determine the stresses in this LP rotor and the next slide will show you that this LP rotor can be looked at as a solid model.

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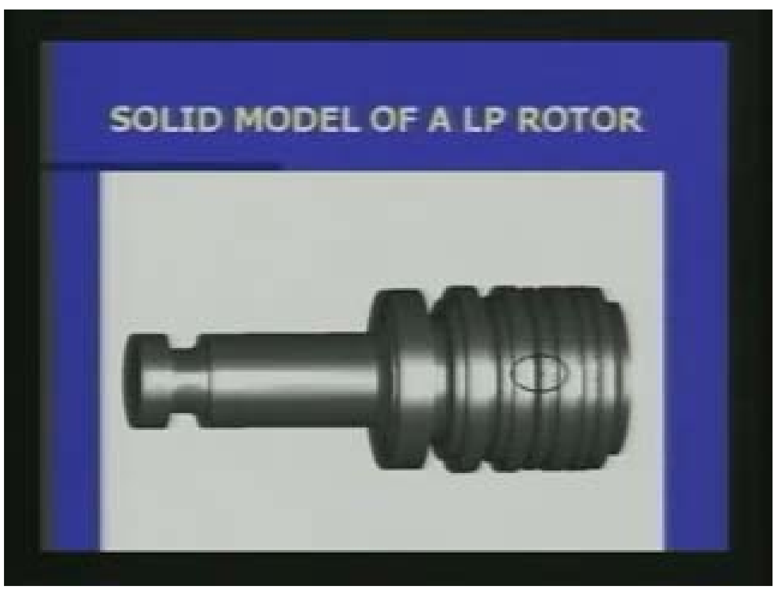

You can also see a small marking in the LP rotor. Actually what happened was that during the manufacture of this LP rotor, there was a small mistake that was done during

CNC programming and instead of machining LP rotor as it is, the LP rotor was machined inappropriately or not correctly. So, a small hole was created which you can see in that particular slide which is been marked by a small ring. You can see that in the next slide in a much more close up fashion.

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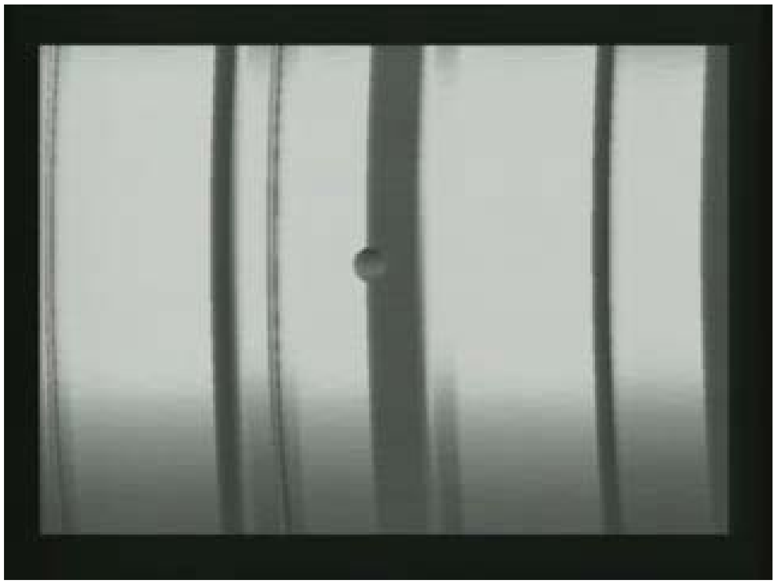

You can see that there is a small hole there. The problem is that this small hole or defect which has been created due to improper manufacturing, it so happens that it is at a place where the stresses are also high. But this rotor being very expensive, it is about 10 crores and the lead time to manufacture this rotor is nearly 6 months which means that a project worth about 3000 crores; a particular thermal power project worth about 3000 crores is going to come to a stand still, a screeching halt for 6 months which means that it is not acceptable.

The whole question here is that can we use a predictive technique a computational method in order to find out whether this mistake can be tolerated. If not can we modify this rotor which has a defect in such a fashion that we do not compromise on the safety aspect of the system. So, that is the question. If we can use finite element analysis in order to pass this rotor, then we are going to save very valuable time. We did this and we can see from the next slide how what is called as a finite element model looks like.

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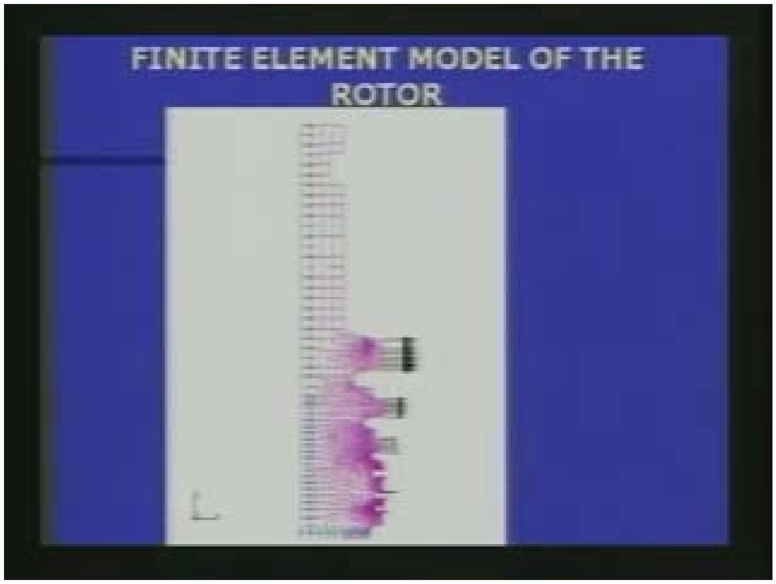

We took into account the centrifugal forces which are very, very important; in fact the rotor is designed for centrifugal forces and you can see those arrow marks there which indicates the position at which the blades are attached.

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In the next slide you can see the stresses. This is for an existing good LP rotor. The whole idea here is that the good LP rotor is analyzed first so that the stresses are determined and when we do for a new or this modified rotor the stress levels that you are going to see here are going to be the same in that particular modified rotor as well. If we do that then we are not compromising on the quality or the safety features. Imagine that it is impossible for you to make this kind of modifications in the actual piece and try it out. In fact we did about 4 or 5 modifications before we came to that modification which is going to be helpful or which is going to be implemented. It is impossible for you to do. As I said it is 6 months lead time and hence computational method is extremely useful in order that such a technique can be used. You can see that in the next slide.

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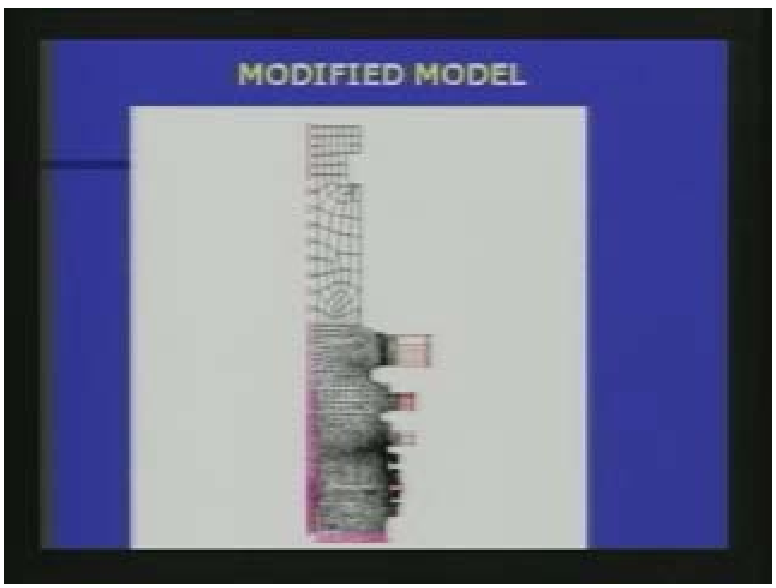

The modified model is better seen in the zoomed up view of the next slide.

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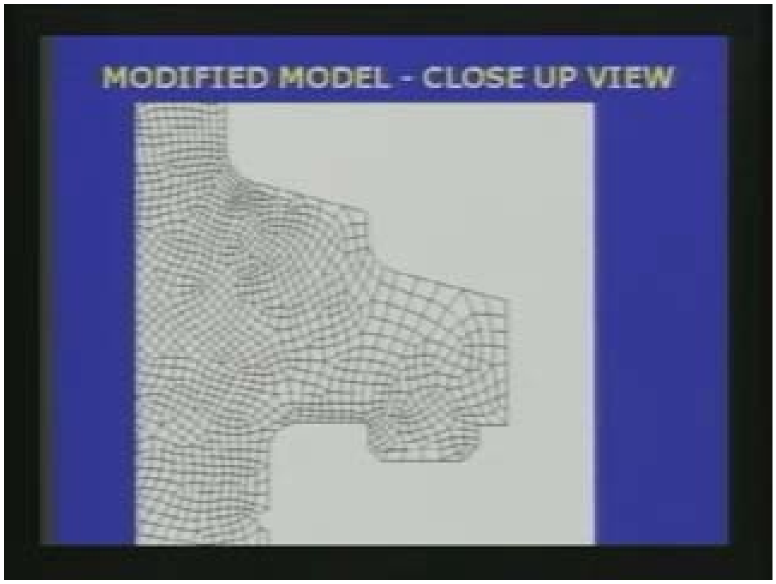

You can see that a small portion has been removed axially, completely; it is an axial piece; axially and again stress analysis has been conducted.

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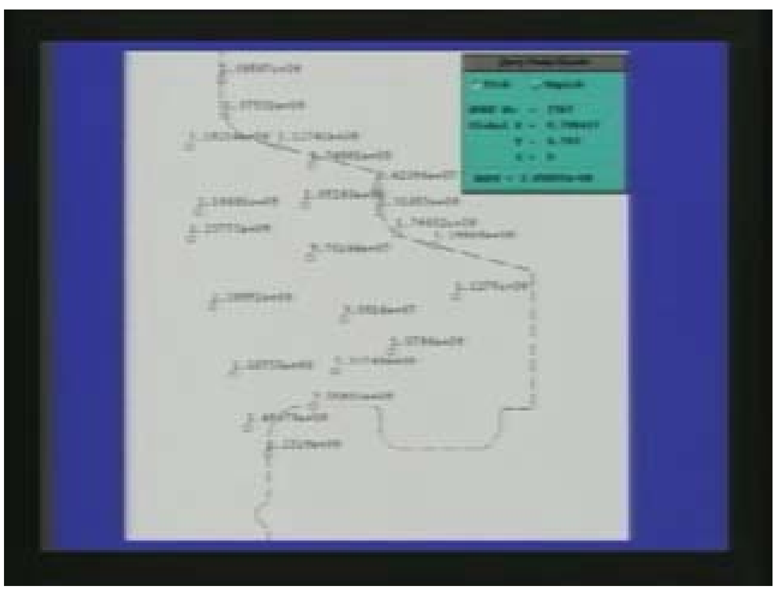

The next slide shows the results of these stresses. Though The stresses are not very significant for you at this point of time. Because we have not talked what are called as Mises stresses, you may not understand right now what are Mises stresses and we are going to explain those things in the course, which we are going to see now. Nevertheless, if you are able to see the numbers, you can see that the numbers are exactly the same, are almost the same which means we have modified it with absolutely total control over quality. So that is a very important example. We were able to do the whole thing in a matter of about 5 days.

What would have taken not even months but years we were able to do that. We did about 4 iterations; we were able to come to this conclusion in matter of about a week maximum. That is the power of computational methods and that is the power of finite element method. Let us look at the next problem which has been done to another company.

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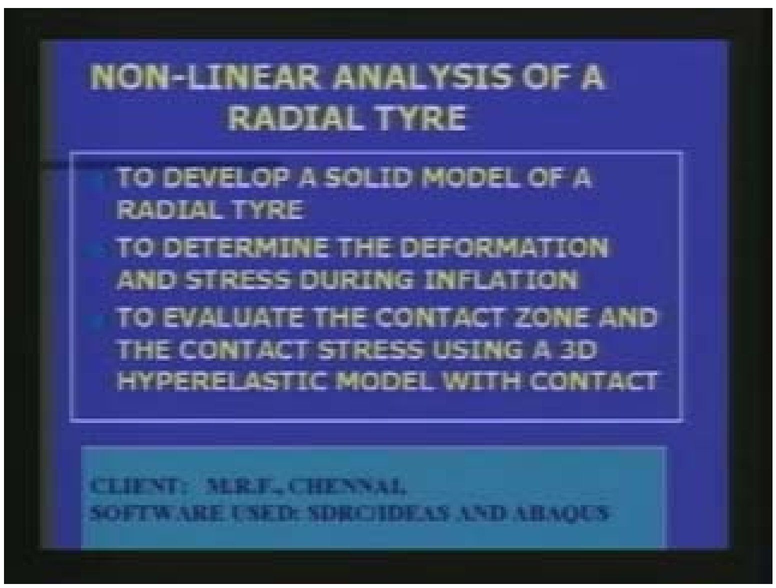

Though the first problem was critical, was very, very critical problem, because as I told you it involves 3000 crores, the problem as such is not difficult because the problem involves only a linear elastic analysis; one of the simplest kinds, not very difficult, geometry very manageable. So, the problem is a delight to do, it is well behaved. On other hand, look at this problem.

We are now going to talk about a radial tyre.

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This is the section of a tyre. It is very, very complex component, extremely complex due to so many reasons. What are the reasons? The geometry itself is very complex; in a minute we are going to see how complex it is. When we did the solid model of this piece we had to put nearly 21,000 surfaces in order to define this particular piece. Number one geometry is extremely complex; not only just external geometry, geometry is also defined by certain internal modifications. You can see that there are some reinforcements that are given.

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This tyre is called a radial tyre. You can see that there are some steel belts or reinforcements that are given in this tyre in order to withstand the extreme conditions that this tyre would be subjected to, as it is in a vehicle. The second point that is important is not only the external geometry but the internal geometry or the internal arrangement of material. The third point that is important is that the material that is used to make this tyre, the material is a non-linear elastic material; it is a rubber, it is a non-linear elastic material. The behavior of the material is very complex. Again towards the end of the course we will also study how to tackle such difficult problems, but right now all of you I am sure know that rubber is a non-linear material or it has a non-linear material behavior, so that is the third complexity.

The fourth is that the tyre is in contact with a number of components. It is in contact with the rim, it is in contact with the ground and so on. Contact makes life really miserable when you look at the computational aspects and rubber or this tyre rather which is a rubber component has contact as well. It has all the complexity; name it, it has it. On top of it, it has to be looked at both as 2D as well as three dimensional problems. Why is that we do it? We will understand looking at the results. Let us look at the first step that we have done with the next slide.

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This is the solid model of the complete tyre. You can see that, as I told you, it has nearly 21,000 surfaces. It has been meticulously done and now we know as to how or what is the procedure that has to be followed in order to create this particular tyre. Though we took about a month’s time to do this work, if you ask me today, matter of about 2 to 3 days it will be possible to produce such a tyre. Let us look at the next slide and see what we have done there.

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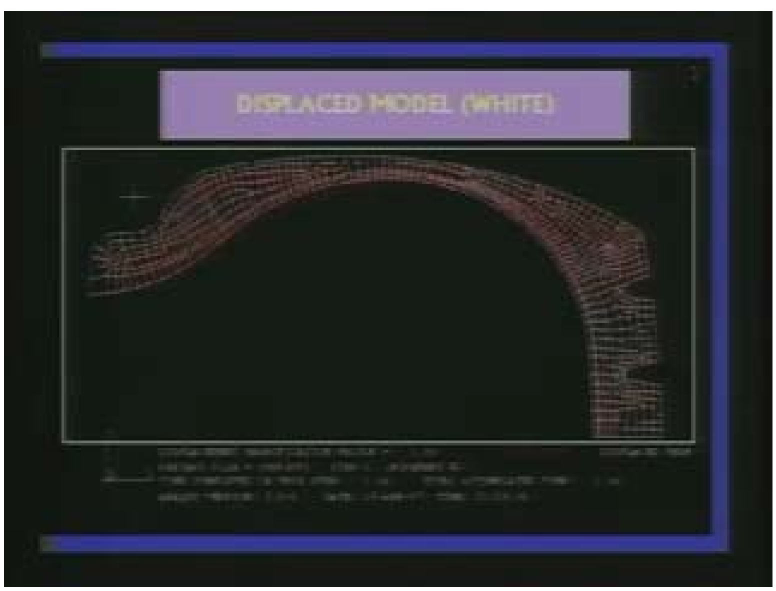

What we have done is what is called as axi-symmetric analysis in order to predict the deformation during inflation; during inflation. What do I mean by that? I mean to say that it is important to realize or understand how the tyre is going to behave due to the inflation pressure. This particular optimization of shape is very important for the tyre industry. Let us look at the next slide and see what we can infer from this slide.

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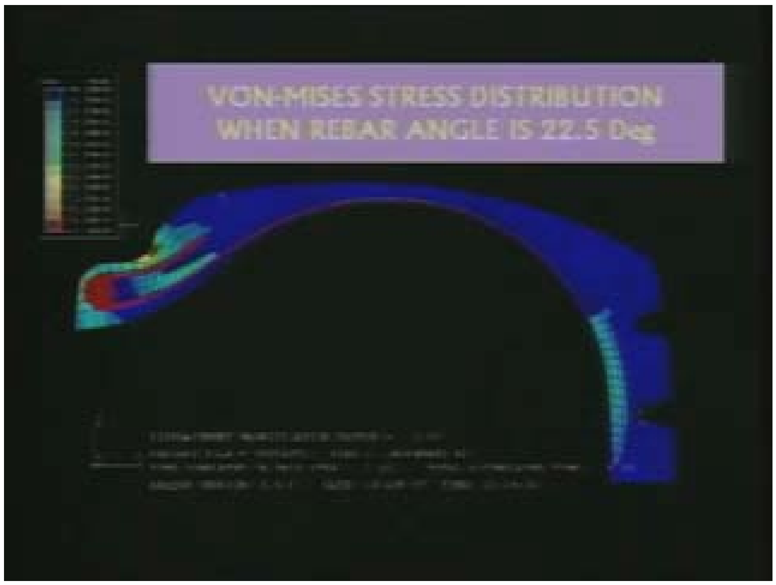

You can see those red marks there. I hope that is very clear. There is one big red area, a circle which is seen to your left as well as a red streak of line that you see. That red area, that circle is called as a bead; that is what is called as bead. You can see it here.

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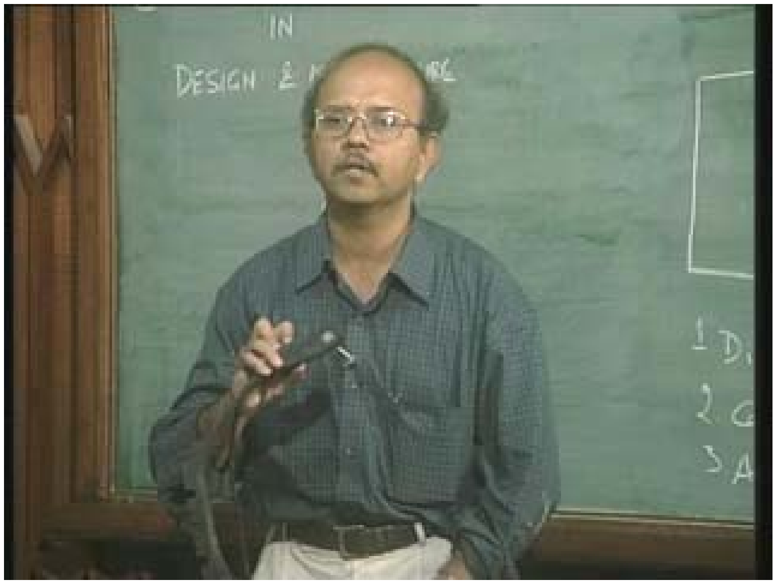

You can see here the bead and the red streak is actually a reinforcement that you can see. That is the reinforcement that is given and what it shows? What does this result show? The result clearly shows that the stresses are quite nicely taken by these reinforcements during inflation so that the rubber does not take that kind of stresses but this reinforcement takes the stresses. As all of you know the stress levels to which a steel bar can be raised to, is much higher than that of the rubber. But we need rubber due to various reasons.

You can see also from that particular slide (Refer Slide Time: 22:26), a small area near this place, near this place where the stresses are higher than other locations. Again you can also see in these locations there are reinforcements.

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There are reinforcements here as well. These reinforcements are again steel wires, very small steel wires which run at around 22 degrees or 20-22 degrees. The whole exercise in this particular example is to find out what is the optimum angle of these steel belts such that the inflation pressure can be very nicely handled; such that the pressure that is developed due to contact of this tyre on to the ground is very nicely dispersed and so on. That is the first part of the story on tyre. Now let us look at the second part of the story.

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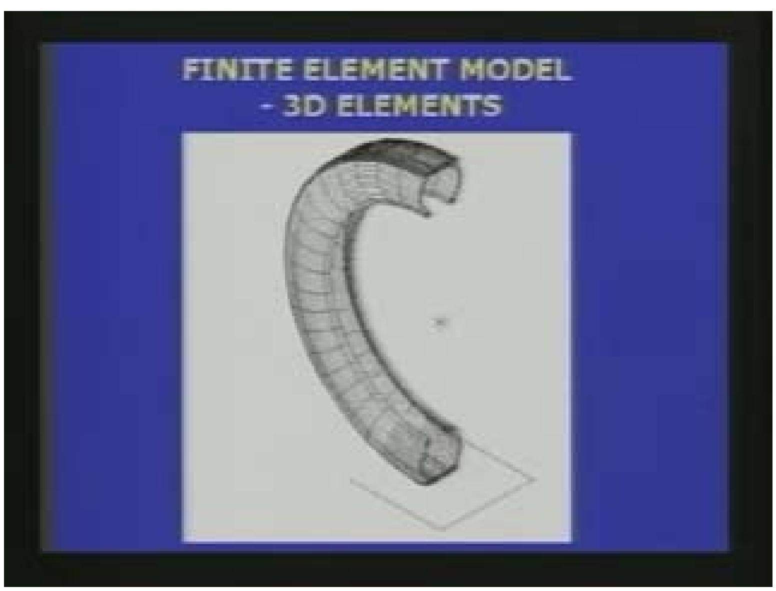

Let us see the additional things that can be done. This is the three dimensional model, a complete three dimensional model of the tyre. You can see that the tyre, complete tyre is not analyzed but only half the tyre is analyzed; only half the tyre is analyzed. Why because we are taking care of correct symmetry. So, only one half is analyzed. We put what are called as boundary conditions in such a fashion that we take into account exactly; there is no approximation. Please note that there is no approximation but we put boundary conditions in such a fashion that we exactly, theoretically take into account the complete piece.

Let us go back and see in a more, say closer fashion how exactly this model looks like. Let us see that again.

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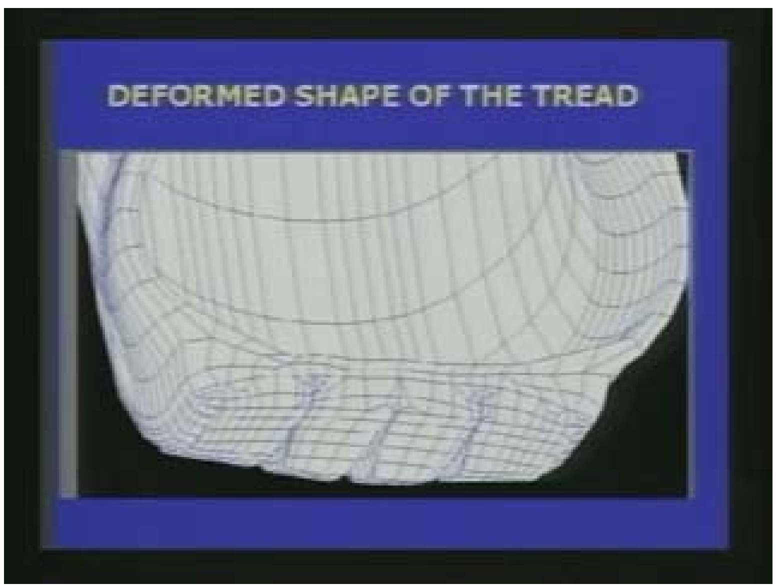

You can see that when we look at this model, we can look at all the grooves in it. In fact this particular slide gives the result due to contact and so on. In fact it would be better again to go back to the previous slide and to look at it much more closely.

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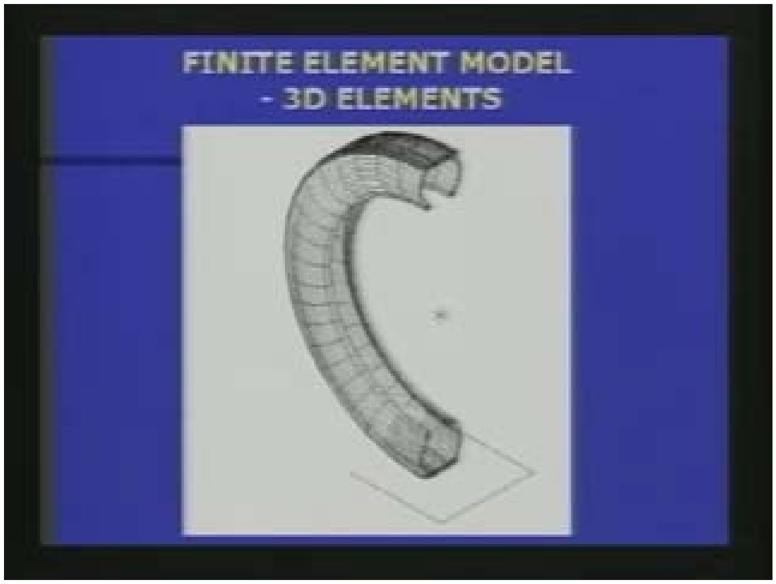

There are some very interesting things that you can observe. You see a small rectangular piece at the bottom where this tyre rests. That actually depicts the ground; that rectangular piece there depicts the ground. There is one center dot; dot at the center. Are you able to see that clearly? That dot at the center actually depicts the rim. When compared to the tyre whose deformations are quite high, the rim as well as the contact surface is considered to be rigid. In other words it is important to understand that in finite element analysis it is possible to combine a very rigid piece like a rim, treat it as rigid, as well as a highly deformable piece like rubber.

It does not mean that I cannot look at contact between two deforming surfaces. But it is advantageous many times to make such engineering assumptions and say that look any way the rim deformation will be very small when compared to the rubber deformation and I am interested in the rubber deformation and hence I will make the rim deformation to be negligible when compared to this and study the problem. That is what makes a model handleable. The question that you may ask is why do you want to make such assumptions? Why is that you want this rim to be rigid? Why not you make that also as deformable? Yes, I can make that deformable. But the problem becomes huge, handling becomes difficult in the sense that this has to be handled in a computer and the computer resources that are required are quite enormous for such a problem. Hence we make some assumptions like that.

You will notice as we go along this course that computer resources, though we have very powerful computers no doubt about it, computer resources are going to be one of the major questions that have to be answered for this kind of high end problems. This particular problem took nearly 40 hours in a very powerful system. Yes, this was possible today with 40 hours; may be 5 years hence this may be possible within 4 minutes and 5 years before I would not have been able to do this problem. It is a question of a compromise today with the powerful systems that are available; yes, they are powerful. Can we solve very, very complex problems and what are the types of problems that can be solved? Many rubber companies or tyre companies rather still use super computers to solve many of those problems.

Since we do not possess so many super computers in India we have to make some engineering judgment; we have to make some assumptions in order to do such kind of problems. Why is it that this problem becomes important? Let us look at the result to understand why we have to do this problem and that is shown in the next slide.

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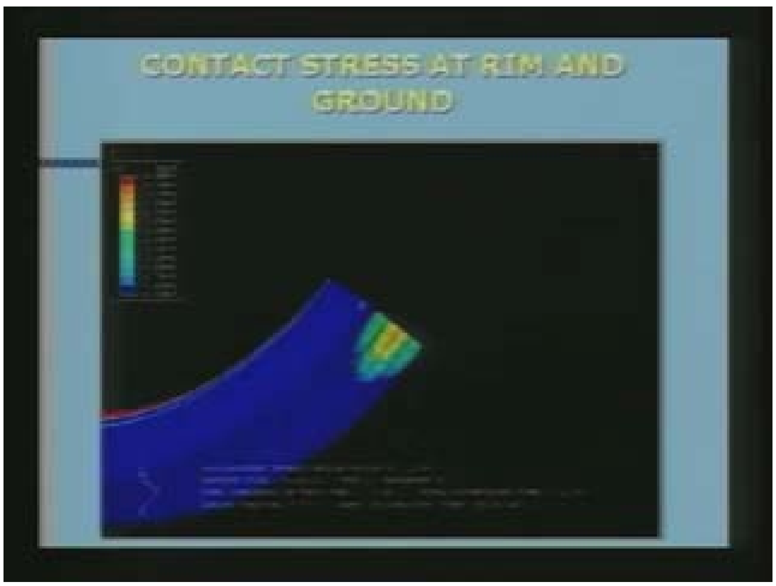

This is the contact pressure; this is the contact pressure distribution. You can see an area which has a different colour when compared to the rest of the areas and this colour changes. You can see green, blue, sorry green, yellow which merges to red. This area is actually in contact with the ground and the contact pressure distribution or the foot print, as it is called in the tyre industry, is very important for them to understand how or why wear takes place or how the design of the tyre can be modified and how the pressure can be much more uniformly distributed.

I do not know how many of you have really seen radial tyres. If you go and look at new cars say for example a Zen car and look at the tyre, a layman would always feel that the air is not enough. You would see the deformation to be more. You would always have a lurking fear is it ok? Is there a problem? You go and check up the air; you would see the inflation pressure to be perfect but still you would feel that the deformations are higher but you need not worry about it. The point there is that the pressure has to be much more uniformly distributed and you know what happens if I just have a line contact. If the inflation is high or if the pressure is concentrated in one or two areas, small area, then obviously the pressure will be high.

Why? Anyway I am going to take the total load of the vehicle. Hence pressure distribution is a very important input for the design of the tyre. In today's competitive world it is almost impossible for me to first design a tyre, test it out, make a mould and test it out. You have to make the manufacturing of this tyre and in order to do that you have to look at or you have to look at ways and means in which you can design, develop, test moulds and so on. It is a question of about 4 to 5 months. I cannot afford to have about six different varieties of moulds, then test them, then make the tyre, then again go back and test this prototype, go and modify them, remake another tyre and so on. You know it is impossible. By that time the car model itself would have changed. Computational methods are very important in order to optimize such products which are very, very complex and this is not the only output that you can get. The previous slide shows a very interesting output as well. Let us look at that.

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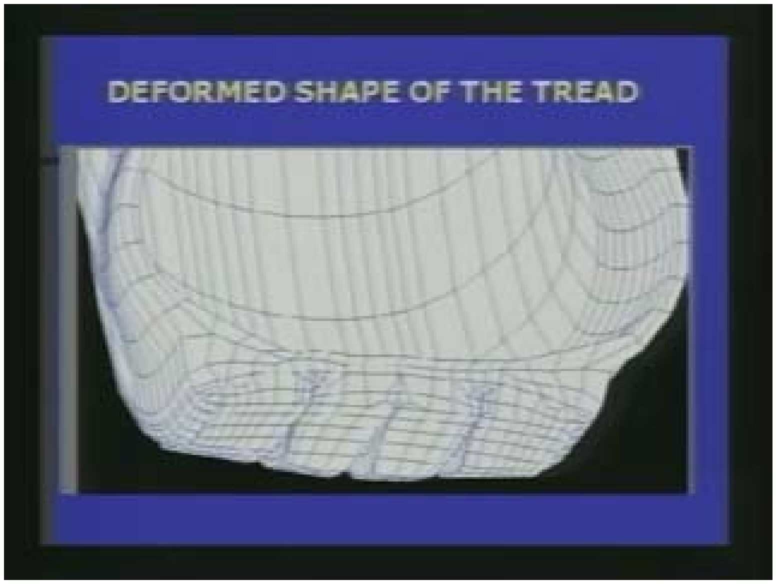

It is clear for you that the treads, as it is called, you can see that there are tread patterns here. The tread patterns are shown in this particular tyre.

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It is very important to know how this tread pattern behaves during the contact, when it is in contact with the ground. Let us go back and see that. You can see that (Refer Slide Time: 31:57) the picture clearly shows that a small gap develops towards the top of the tread when compared to the bottom. In other words the bottom of the tread gets closed or buckles whereas there is a small opening at the top. This may lead to problems when the vehicle goes over water. The water may get in. There can be some sort of a hydrodynamic lubrication and so the vehicle may start skidding. There should be ways and means by which you can eliminate this water which is sitting inside. This is called as aqua planning. You can get very important input from this kind of deformations that you see in this particular output. From a very simple component to a very complex component like tyre, it is possible for us to look at the computational technique in order to optimize our design.

Let us go and look at some other example. We will see what are the other things that can be done with finite element analysis?

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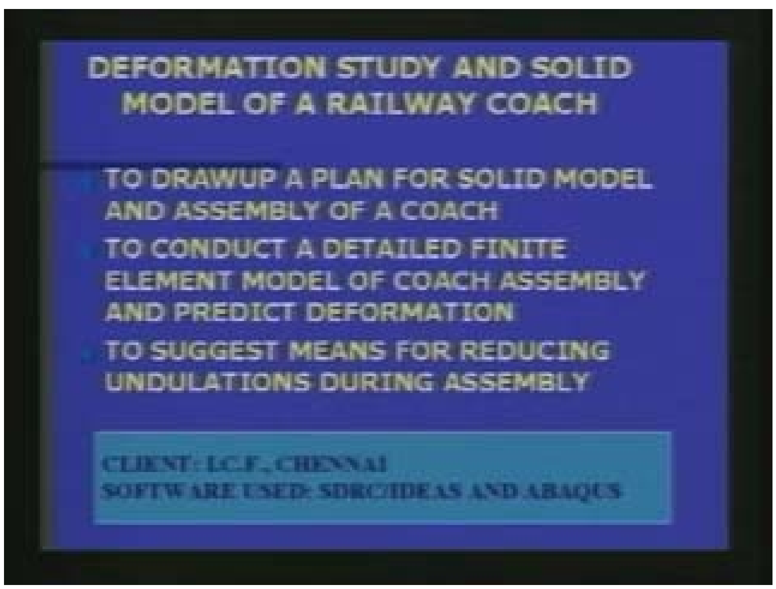

We are going to look at a much more complex component geometrically, very complex component geometrically and what we are going to do here or at least what we are going to see right now, we will come back to this example towards the later part of the course, but what we are going to see right now is that a complex piece like a railway coach can be done in a computer or can be modeled in a computer. The whole of manufacturing process which is used to make this particular coach can be simulated in the computer beforehand and we can learn so many things by doing the simulation. What is that we are going to learn? Let us look at the first slide and see what it teaches. Let us now see the model.

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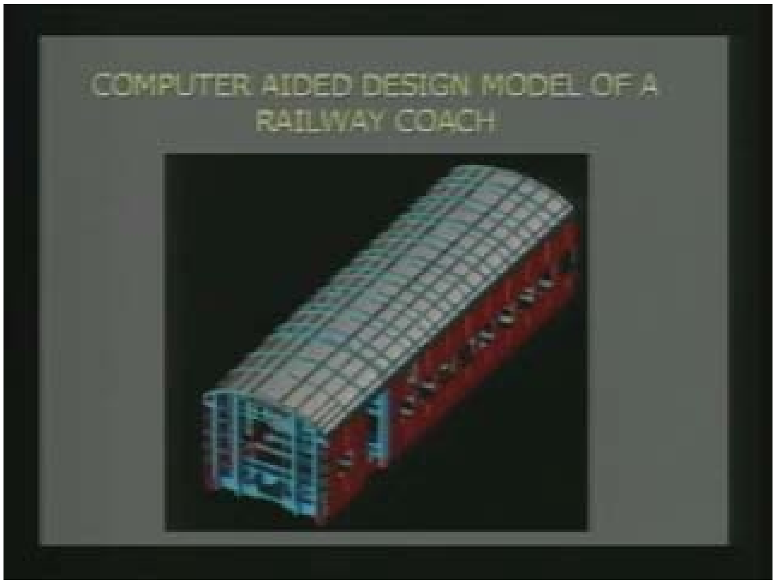

This is what is called as a computer aided design model of the entire coach. See how realistic it is. Many people have asked me if it is a photograph or is it really a model. It is so very realistic. There are about 250 major components which go to make this coach, which actually takes the stress and strain of travel, of payload and so on. Our model is put into this particular model. You can see that again and you see that the whole coach is divided into three different areas; the roof which is shown as white, the side wall which is, of course all of you know it looks, red and the under carriage on which all of us sit and travel in the train.

One of the problems that our Indian coaches have is the lack of very good aesthetic appearance. All of us have traveled by train and maybe you would have all noticed some undulations on the sides of the coach. Have you all seen it? Especially when you go to the station and in the evening times or night times when there is light, it is very clear that there are undulations on the sides. Though if you look at the performance of the coach this kind of undulations are not going to affect but aesthetically does not give a very nice look. If especially when you want to import or sorry export this kind of coach people are not going to accept with this kind of undulations. We have to take care of these undulations. These undulations are unfortunately part of the manufacturing process or it comes out because of the way coaches are manufactured. It is not very easy to change that. I can say that it is because of the way in which it is manufactured; it does not mean that I can give you a complete alternate way of manufacturing basically because you should understand that these sheets which have undulations have a thickness of around 2 mm; see how thin it is, 2 mm thickness.

Basic manufacturing process is a welding process. Due to assembly and welding these undulations creep in during manufacturing. Yes, the first part is understood; but there are so many intricate details that can be looked at during manufacturing and which have to be understood and which have to be segregated in order to understand why this kind of undulation is coming or other words is it possible to pinpoint out of some 10 reasons what is the most important reason which causes this kind of undulations? That is not very easy to do in a shop floor. We have in fact tried it out and it is not very easy to do it in the shop floor. On the other hand it is possible to do that in a computer using finite element method.

Let us go and have a look at that and see whether it is possible to predict this kind of manufacturing process as well as the undulations. Let us look at that in the next slide.

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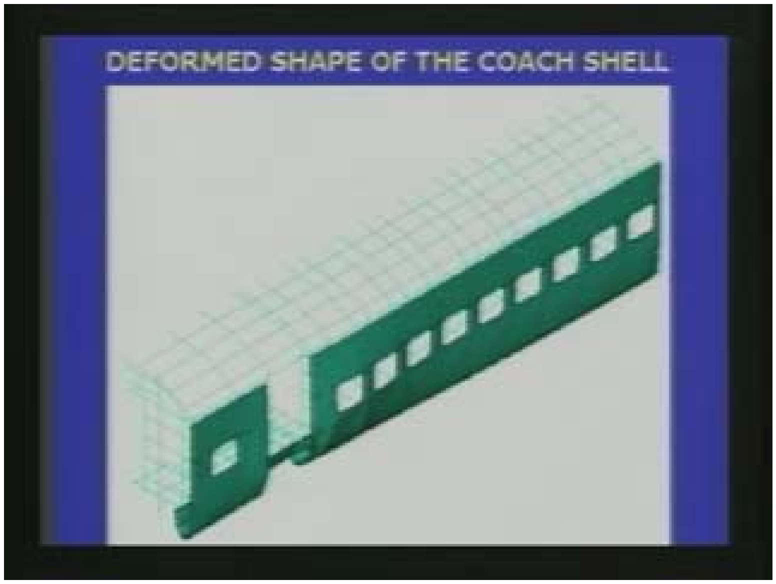

This is the result. We are not looking at how to do it; that we will do it later, but this is the result of the analysis. You can very clearly see the undulation step. In fact the next slide shows it in a much more closer view. You can see the zoomed up view of that in the next slide.

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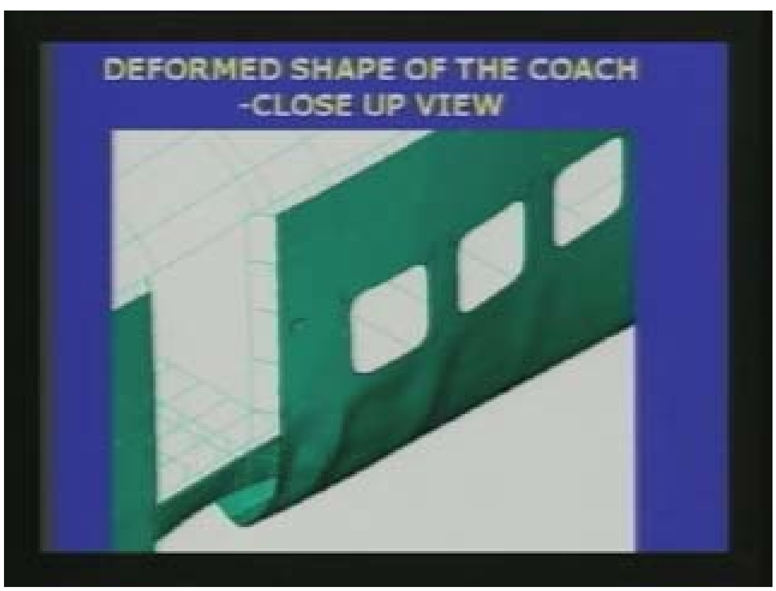

Look at that; though it is a magnified view you can see that the undulations are very clear; undulations are very clear. These undulations are due to the assembly procedure itself. As I told you it is impossible to change that. But there are ways and means by which you can change the design and reduce these undulations. More importantly it is possible to predict such very, very intricate details that you come across during manufacturing in computational methods or by using finite element method.

Let us now look at the next problem which is again a very interesting problem.

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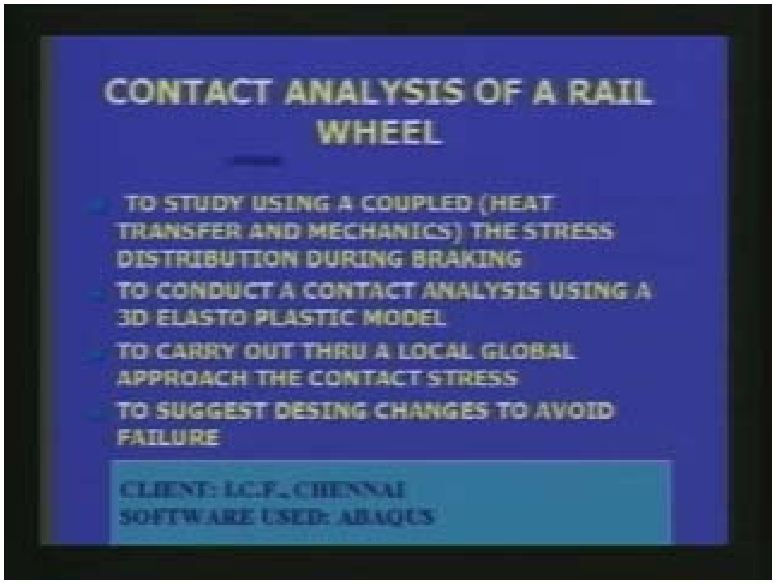

The next problem that we are going to look at is what is called as the contact analysis of a rail wheel. All of us know railway vehicle coaches and all these things very well and all of us know that the rail wheel is subjected to lot of stresses as bad or as good, however you wish to call it, as that of the tyre. Though, geometrically the railway wheel does not seem to be as difficult as that of a rubber tyre, there are other difficult things that you would also notice in the analysis of a railway wheel. The analysis of the railway wheel is very well documented; the analytical procedures are very well documented. There are standards which are used to design the rail wheel.

But in spite of all these things, there are quite a few problems. If you follow the newspapers probably you would have heard that there were some accidents, railway accidents last year in Euorpe. In Germany there was a railway accident and probably if you keep your ears open you would have heard about some rail wheel failure in certain metros and so on. In other words rail wheel failures are still common and in India, there have existed some failures in metro cities and the whole idea here is to check up, to find out what is the reason for such failures. Can we see or can we really predict them by using finite element analysis and take corrective action?

Though surely the railway wheel are very, very safe but today we no more talk about percentage, we talk about parts per million; failures in terms of parts per million. In other words, we do not even tolerate one failure out of million. We have to be very safe especially in the case of air craft; in the case of railways and all these things we have to be extremely safe. You need not worry about that. When I say that there have been failures, it does not mean when you go and sit in a vehicle you have always a lurking fear that whether the wheel will fail or whether the coach will fail and so on; not like that. But nevertheless, as engineers, we have to make this kind of public transport systems as safe as possible and hence it is better that we understand what exactly happens in this kind of wheels?

Let us look at that in this particular slide.

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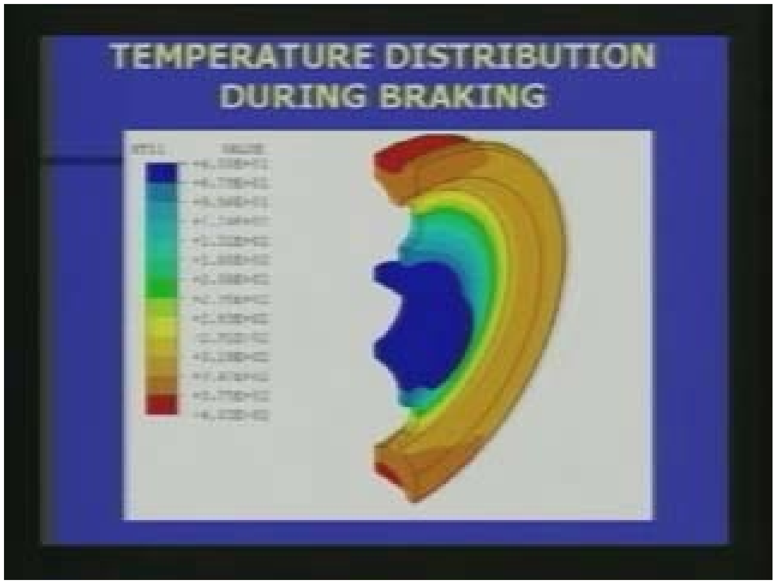

This is actually the temperature distribution during breaking. In many of the vehicles or emu's or electric coaches which run in metros, you would have noticed that there are number of stations and that braking in these vehicles are quite often carried out; all of you know that. From one station to the other, the guy just accelerates and then he has to decelerate and apply brakes. In such circumstances, it is very important to understand the temperature distribution during braking and this can be solved using finite element analysis.

It is not only the stress, we saw that stress can be determined; not only deformation which we saw in the previous experiment or previous example that deformations of the coach can be determined. The stresses are obtained from deformations. We are going to see that in this course; deformation is the first step towards going to the stress but deformation per say are important in certain problems and now you see that temperatures can also be predicted. You see in this particular slide that the temperatures can be predicted. Let us worry about how to do it later but let us only look at the result.

You obviously see that the outer side of the wheel has maximum temperature but it does not mean that the outer surface has maximum stress. We will discuss this problem again and look at what are the complexities that are involved in this problem. But at this point of time it is important to understand that from this temperature it is possible for me to predict what the stresses are or in other words using finite element analysis I can also look at coupled problems; temperature giving rise to stresses and vice versa; stresses giving rise to temperatures as well. These kind of coupled problems can also be looked at using finite element analysis.

Let us look at the next slide for this railway wheel.

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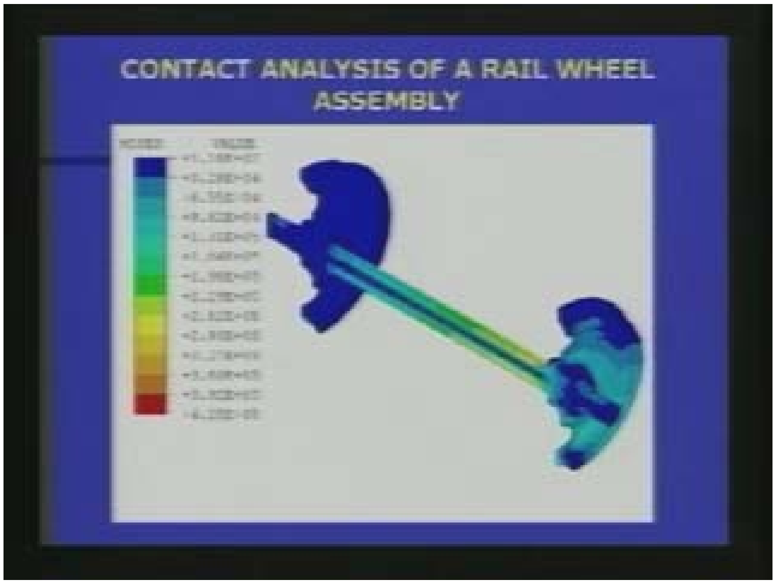

You can see again that the contact analysis of the railway wheel becomes important. Apart from temperature, the contact analysis or the contact or the stresses, the strains that exist because of contact of the railway wheel with the rail also becomes important and that can be seen in a very close up view in the next slide.

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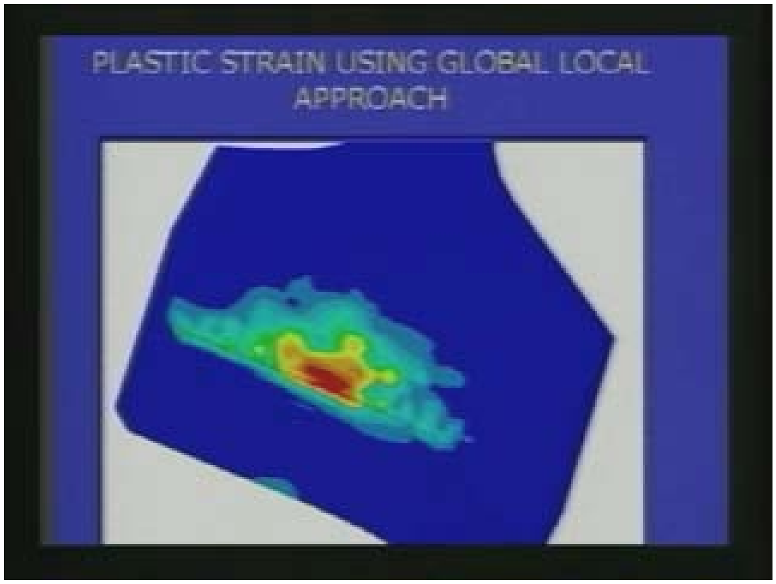

Look at the plastic strain that exist very near the place where the wheel is in contact. For this particular problem not only are we determining the displacement, we are determining the temperatures. We are also determining the contact plastic strains which may become very important to look at there and so on. So, many, many important inputs, important from a design point of view can be obtained by using techniques like finite element analysis. We will come back to this example and further examples in the next class. But, before that let us see the types of inputs that we give in order to do these problems. Can someone come out and say what are the type of inputs that are required in order to solve this kinds of problems?

Boundary condition; yes, boundary condition is important but before that, no; we are not looking at finite element input; input from a designers point of view. Dimension that means geometry; that is number one, the geometry becomes important.

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That is the first input. The second input is the type of force that is acting on this geometry. What is the type of force, how much and so on. The forces are important. Thirdly as you correctly said what are the boundary conditions? Usually we call this as BC or boundary conditions. These are the major inputs. It is easily said than done, there are some complexities in each of them. As we go along we will see that when we look at a complete model, we have to properly take into account each of these things.

We are going to make some assumptions. As I clearly said that the assumptions are important in certain problems as that of the tyre. As we go along we will see how we can take into account these things to complete the problem. Yes, the other problems being what the type of mesh is, how big it is and all that. But we have not yet talked about the mesh. We have only looked at what is a problem, what is the type of solution or output that you can get using finite element analysis in order that it will be useful to the design; that is all we have got. We have not yet talked about the correct or the complete technique or correct way of doing this problem; that we have not talked about. That requires lot of input from this course and that is what we are going to do in this course. We will stop at this point in this class and we will continue on certain other examples in the next class.