Engineering Mechanics
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Module - 01
Lecture - 03
Equilibrium II

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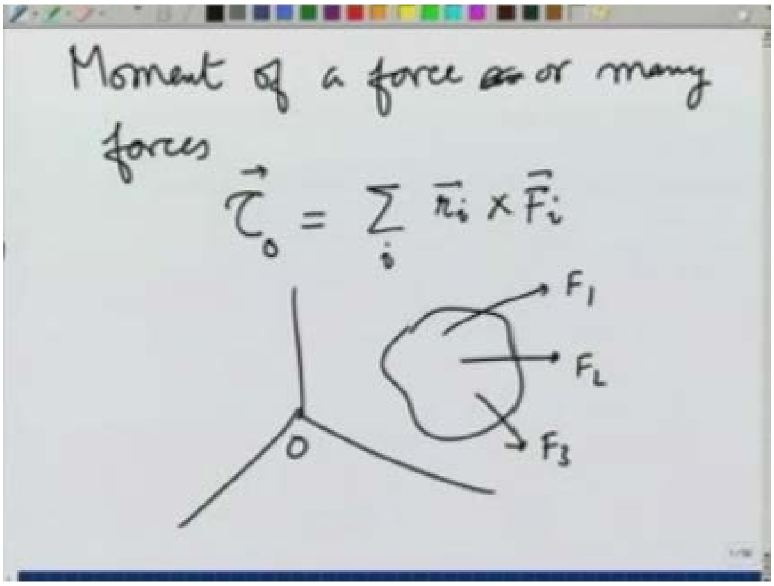

We have been learning about the moment of a force or many forces what we have learned. So, far is that the torque about origin O. So, that I will indicate by this is ri cross Fi .Where we are applying these different forces F1, F2, F3 and so on about point O. We have also, learnt that the torque is origin dependent.

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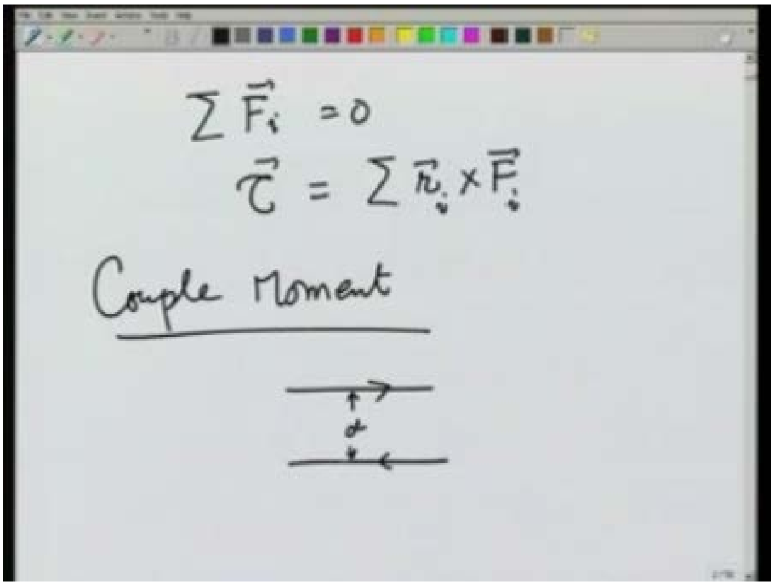

This is a very special case when the total force on the body is 0. Then, torque is independent of the origin no matter about which point it is taken it comes out to be independent. Then, as a very special case of this we defined a couple moment which is nothing but, 2 equal and opposite forces separated by distance d. In this lecture we study moment little more will define the moment of a force or a torque about an axis.

Then, I will give you an example to show you what you have been learning in twelfth grade and our definition is the same. Then, we go on to discuss the different elements in mechanical systems or civil engineering systems and what kind of forces do they apply with examples. So, we are going to study in this case the moment of a force about an axis.

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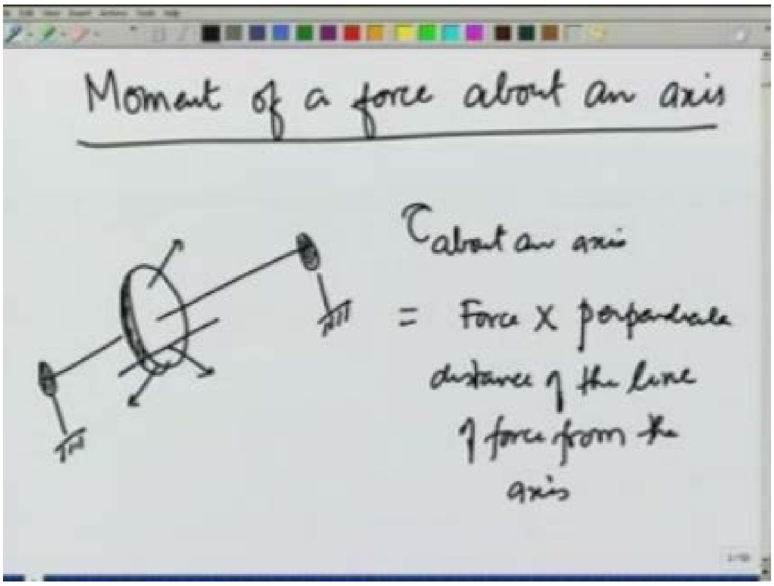

Why this is important is, a lot of times for example: you have situations where something they actually made to rotate about an axis this axis of a rotating disk. I may have fixed in ball bearings which are fixed in some place. In that case no matter what force you apply on the disk the only component that is responsible for its rotation is that in the plane of the disk.

Then, if you recall your twelfth grade physics you have been defining torque about an axis as force times the perpendicular distance of the line of force from the axis. Now, you will get more sophisticated now that we have mastered the vector algebra and so on.

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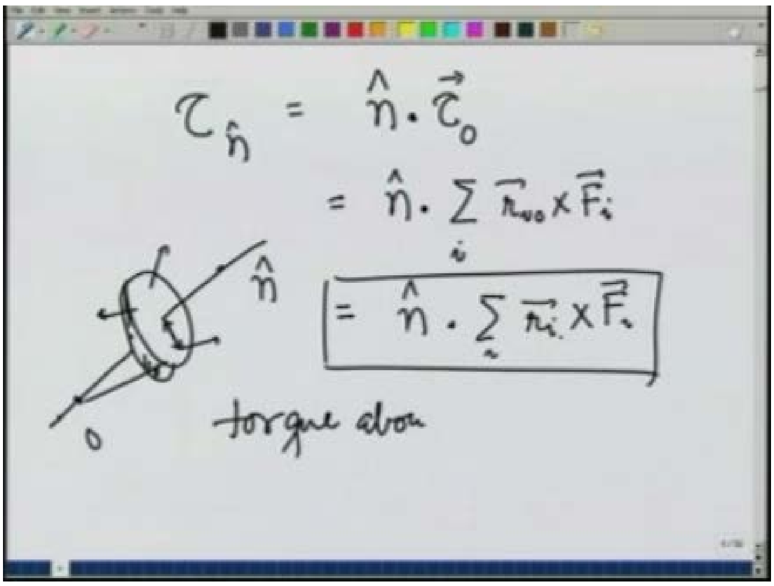

So, define, the torque about an axis in a slightly different manner which I will show through an example is equivalent to what you have been learning. So let us say, there is a disk which is rotating about a fix axis which is in the direction of unit vector n. So, there are various forces working on it.

Then, the torque about the axis n is going to be equal to the dot product of n with respect to the total torque about say the origin o. All though I am writing origin o, the torque about an axis is actually independent of where this origin is taken. Because, it only depends on the perpendicular distance of the forces from the axis.

So, this I can write as n dot summation i rio cross Fi n to emphasize that this is really independent of the origin. I will write it further as n dot summation i ri. I removed this index o cross Fi. This is the component of the total torque along the direction of the axis and this is what I will call the torque about axis. Let us say, n. If you really work it out what is happening is since, the axis is fixed it is held by certain forces, no matter what forces you apply on the disk. The forces generated at the point where the axis is being held are such that they will cancel certain and the applied forces certain components of them.

So then, only force that is responsible for the rotation of the disk about this this given axis is that which is in a plane perpendicular to this axis which is in a plane perpendicular to this axis and more effective it is if it is further away from the axis. This you know from intuition and form you whatever you learn in your twelfth grade.

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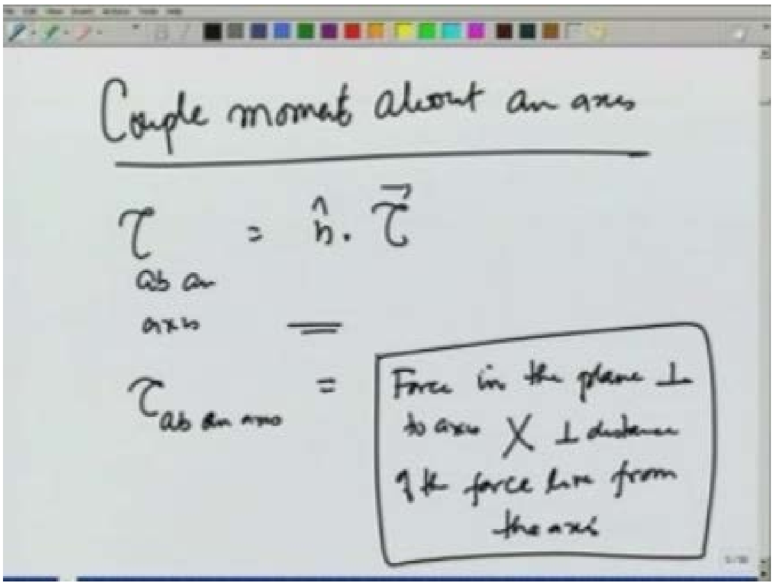

In a similar, manner the couple moment about an axis is the couple moment tau dot n tau about an axis exactly same thing as torque. Because, tau couple moment is nothing but, is very special torque. Let us now see, if this sets well with our definition of torque about an axis is equal to force in the plane perpendicular to the axis, times perpendicular distance of the force line from the axis. This is the definition you have learnt in a twelfth grade.

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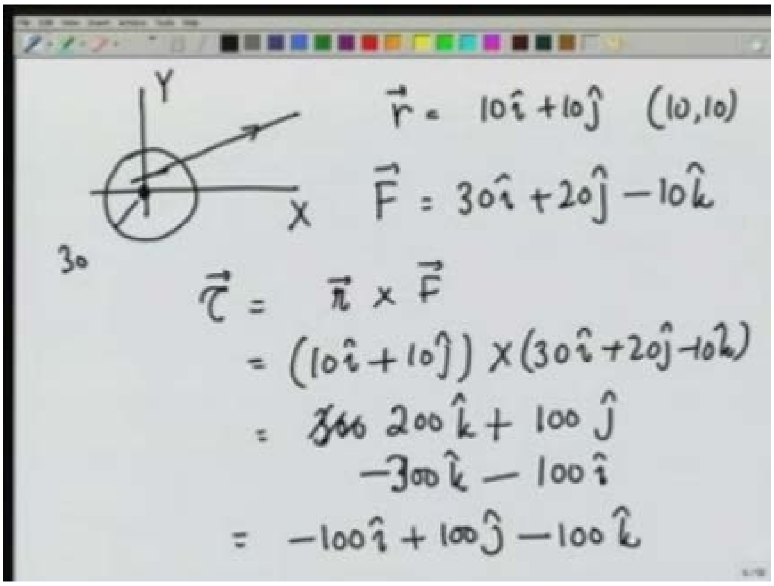

So as a simple example let me take, a disk which is free to rotate about the z axis. Let us say, this is the x axis this is the y axis and z axis is coming out of the plane. Let, the radius of this be 30 centimeters and let me apply, a force at point r is equal to 10i plus 10j in XY notation it is a point 10, 10. A force which is let us say, 30i plus 20j minus 10 k. So, I am applying a force at this point which is like this in the plane of XY and it has a Z component also minus 10 k.

So therefore, going into the plane of this spot; the torque, total torque due to this force is going to be equal to r cross F. Again I emphasize recall from a previous lecture that this r could be anywhere along the line of action of this force. Right now, we will take r to be 10i plus 10j. So, this equal to 10i plus 10j cross 30i plus 20j minus 10k. Let us, work it out and it comes out to be you know 3i cross i is 0. So, 200i cross j which is k i cross k is minus j.

So, minus minus plus 100j j cross i is minus k. So, minus 300k and j cross j is 0 j cross i j cross k is i so, minus 100i. So, this comes out to be minus 100i plus 100j minus 100k that is the total torque, But I want to find the X the torque about axis Z. Because, this disk is free to rotate about the axis Z. So, that torque… so let me make the picture again where is disk the torque came out to be minus 100 this is minus or plus minus 100i plus 100j minus 100k torque vector.

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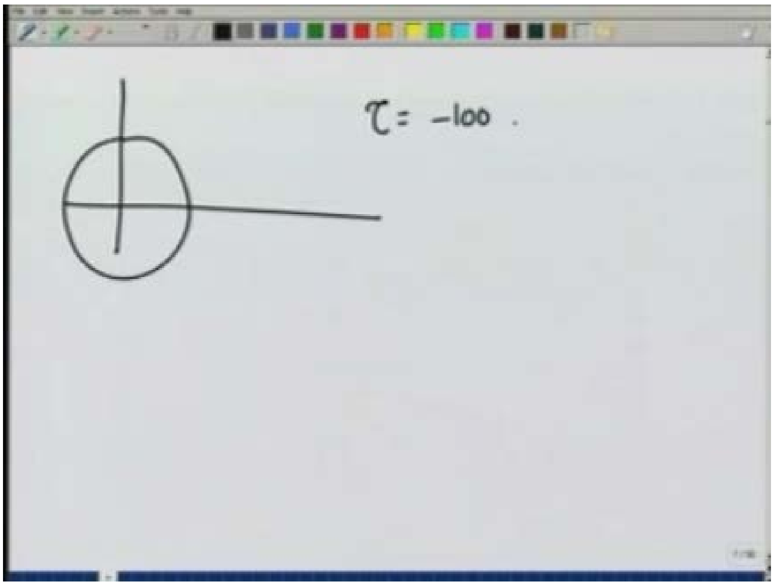

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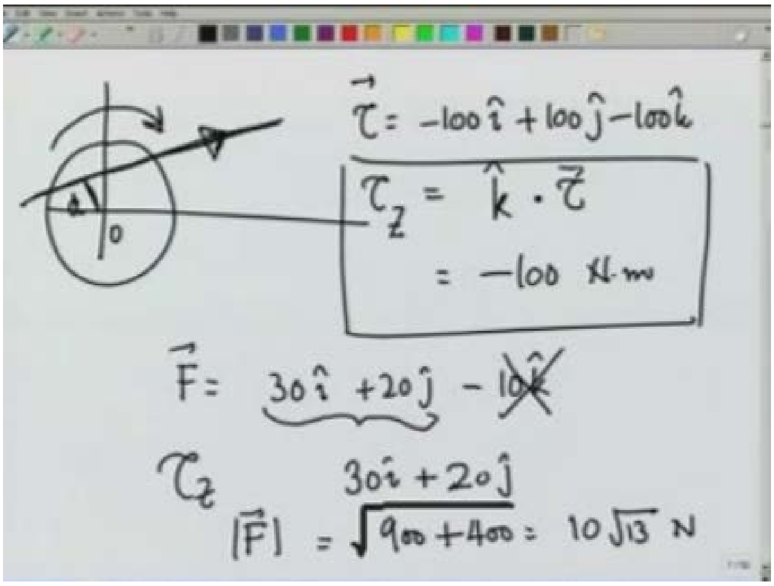

So, torque about Z is going to be k dot the torque and which is going to be minus 100 Newton meters. Minus sign means that this is pointing in the direction of opposite to z. Therefore, the disk tend to rotate to the right hand route in the clock wise direction. This is the sense of rotation of the disk due to this torque.

So, torque about z is coming out to be minus 100 Newton meters. Let us see, if this is consistent with what we have been learning in our twelfth grade. So, the line of force along which the forces working is this. The force is 30i plus 20j minus 10k. As I said earlier the only component of force that is responsible for rotation about the z axis is that in the plane perpendicular to the axis only these components.

So, it is only these two components or the force in the plane of x and y that is going to be responsible for the rotation of the disk. And therefore, 1st thing we do is for tau about z we ignore this force the component of the force along the z axis it cannot apply any force about the z axis. So, tau about z is going to be given rise to by 30i plus 20j. What is the magnitude of the force? It is 30square plus 20square.

So, that comes out be 900 plus 400 that is 10 the square root of 13 Newton's in this direction. I want to find the distance perpendicular to this force that is resistance d from the origin. Let us, find that let me make the picture again. So, as far as the rotation of disk is concerned a force is acting on this of the magnitude 10 square root of 13 Newton's. Along this line which is given by the vector 20,30i plus 20j minus 10k this we have ignored.

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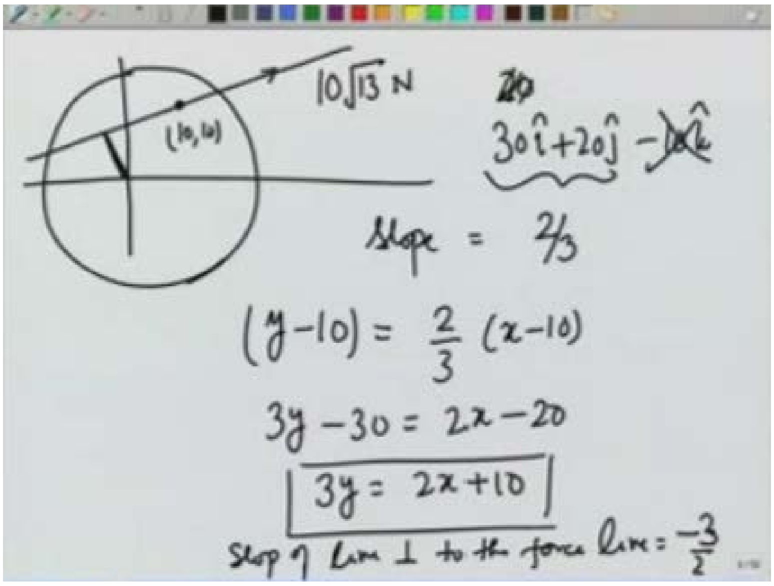

So, in the plane XY this is given by this. So, this line has a slope of two-thirds. And it is passing through the point 10, 10. Therefore, the equation of this line along which the force is working is y minus 10 is equal to two-thirds that is the slope times x minus 10. And therefore, 3y minus 30 is equal to 2x minus 20 or 3y is equal to 2x plus 10. I want to find this distance along the line perpendicular to this force passing through the origin. And therefore, the slope of line perpendicular to the force line is going to be minus 2 3 over 2.

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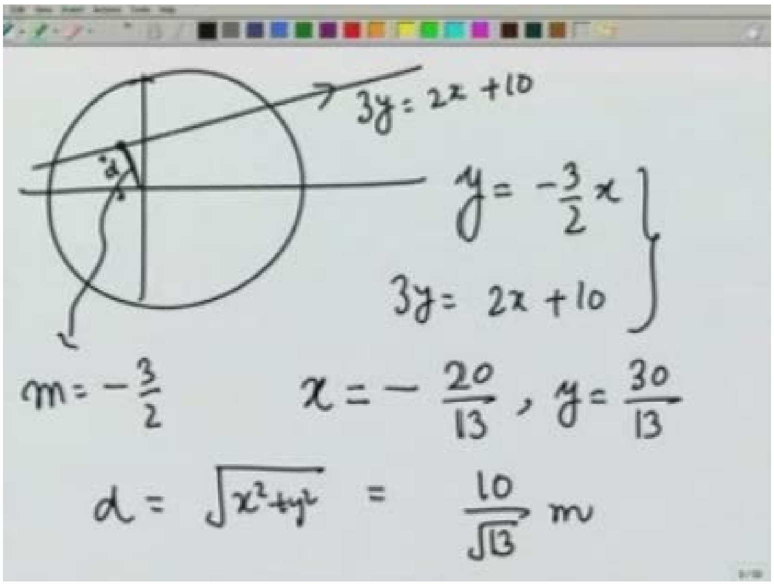

Let me, make the figure again this is the disk here is the force acting and I am interested in this distance the slope under the equation of this line 3y equals 2x plus 10. Therefore, the slope of this line m is going to be minus 3 over 2 and it is passing through the origin. Therefore, the equation of this line is going to be y equals minus 3 over 2 x. The line along which the force is working is 3y equals 2x plus 10.

Therefore, I can find out what the inter section point is you work it out and you will find that x comes out to be equal to minus 20 over 13 and y comes out be equal to 30 over 13. And therefore, this distance d perpendicular from the origin or the axis of rotation to the force line is going to be equal to square root of x square plus y square which will be equal to 10 over root 13 meters. So, we have F we have d and therefore, the moment and therefore, the moment can be found out.

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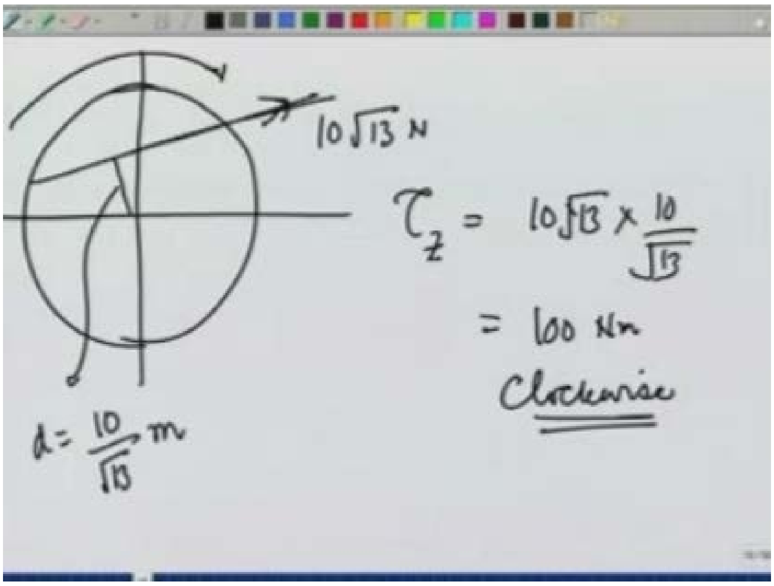

The forces like this whose magnitude is 10 square root of 13 Newton's. We have found this distance which is d is equal to 10 over 13 meters. And therefore, the torque about axis z is going to be 10 root 13 times 10 over root 13 which is 100 Newton meters and because, of the direction of force being this way the sense is clockwise. This is exactly the same as we found earlier which was coming to be minus 100 Newton meters. So, you see the 2 definitions are consistent.

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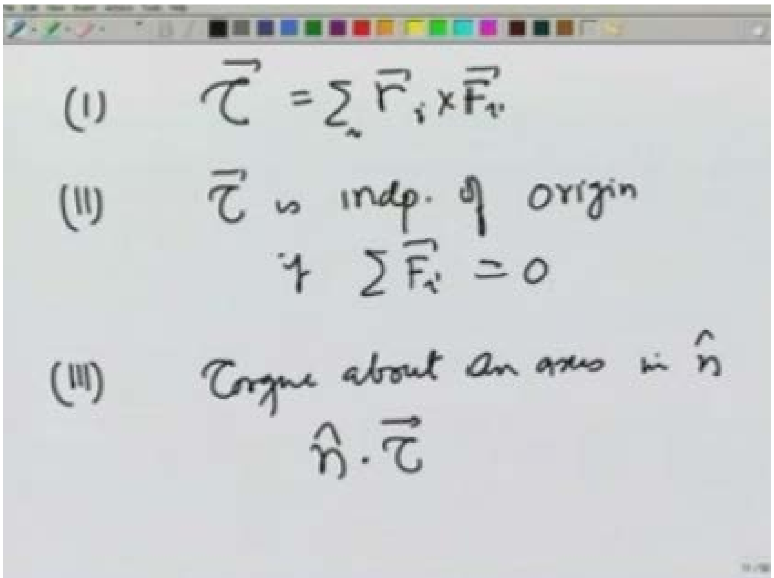

So, let me now summarize what we learnt about torques. Torque 1 is equal to ri cross Fi summed over 2 torque is independent of origin. If summation Fi that is the total force on the system is 0.Third that torque about an axis in vector direction unit vector n is dot tau. Next, what we will do is using the couple moment and force we like to transfer a force parallel to itself and see the effect of a force how it is seen at some other point.

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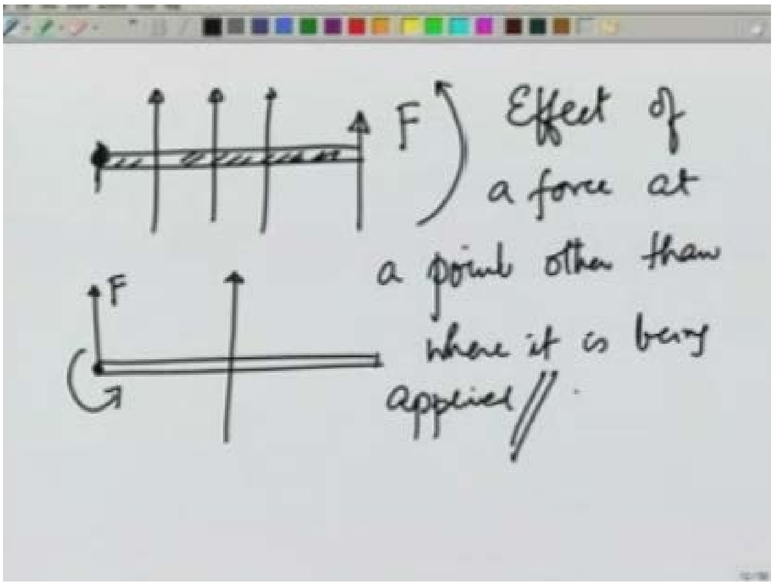

For that let me, just motivate you by taking rod and apply a force here. If this rod is fixed here what you will see, is that this force will number 1 push the rod in this direction and will also tend to rotate it like this. What I want to find is what if I think of this therefore, as a force pushing rod in this direction what else can I do. I will replace this whole thing by a force at this point and a moment that is rotating the rod the is the total effect of the force.

So, what we are going to learn is effect of a force at a point other than where it is being applied equivalently in some books you will see this is called transferring force parallel to itself. And why this is important is, at times you want to really see the action of the force by describing it’s what all can it do can a rotate things, can it transport can move things, accelerating and so on.

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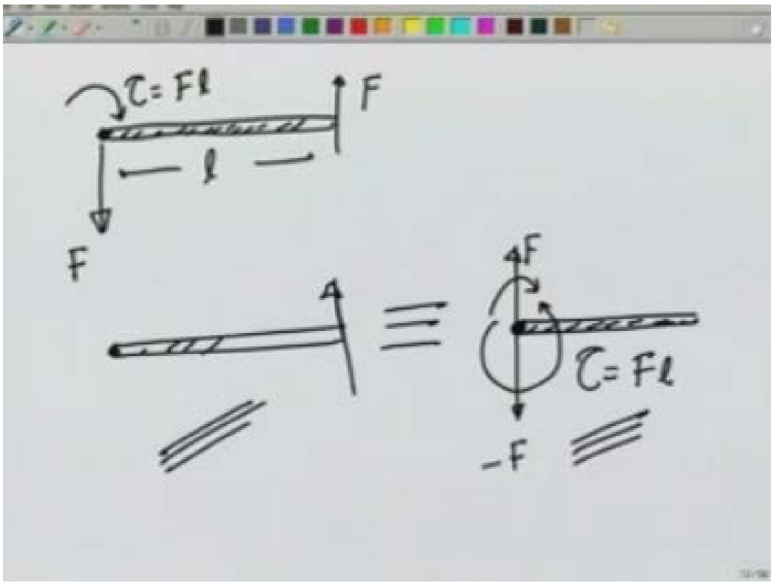

So, this in the example I took if I take a rod and apply a force here F. Let us say, the length of the rod is l and it is held this point. And suppose, the rod is in equilibrium. Then, you would say that I need to apply an equal and opposite force F in this direction and because, these 2 forces produce a couple. I need to apply a torque in this direction which is of the amount F times l to keep the rod in equilibrium.

In other words, what I can say is that this force is absolutely equivalent to a force F at the pivot point and a torque like this of the amount tau equals Fl and a force F. So, that if I want to keep this rod in equilibrium. I need to apply at this point a force minus F and a torque like this. So, this is absolute this is equivalent to this as far as equilibrium or statics of this rod is concerned. How do I understand this?

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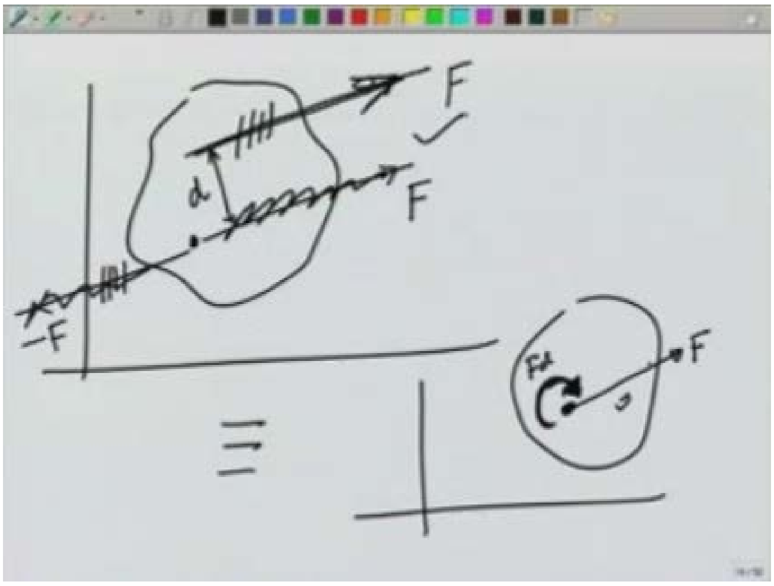

So, let me take a system and let us say it is free to rotate about this point it is held here. And I apply a force like this F let me, now add the 0 force. But I very carefully chosen 0 force on to this rod I will apply a force in this direction. An end in this direction of the same amount as F which is a 0 force F in 1 direction and equal and opposite force at the same point So, I have really done nothing to this.

But, now you notice that the original force and minus F give a couple which is equal to the perpendicular distance between the forces times the force itself. So, I can say that this whole thing is equivalent to applying a torque at this point of the amount Fd and applying the force F in this direction. What I have done is transferred the force parallel to itself to this point. And consequently have generated to keep the entire dynamics or a statics the same I had to apply an addition torque here.

The effect of these this torque and this force these two elements is exactly the same as the effect of that single force original force applied here without these on the body. So, this is called an 2 equivalent systems. It is easier to at times to think in terms of couples and forces and therefore we do this. Let us, take an example you must have seen in buses the handle to change gears is of a funny shape.

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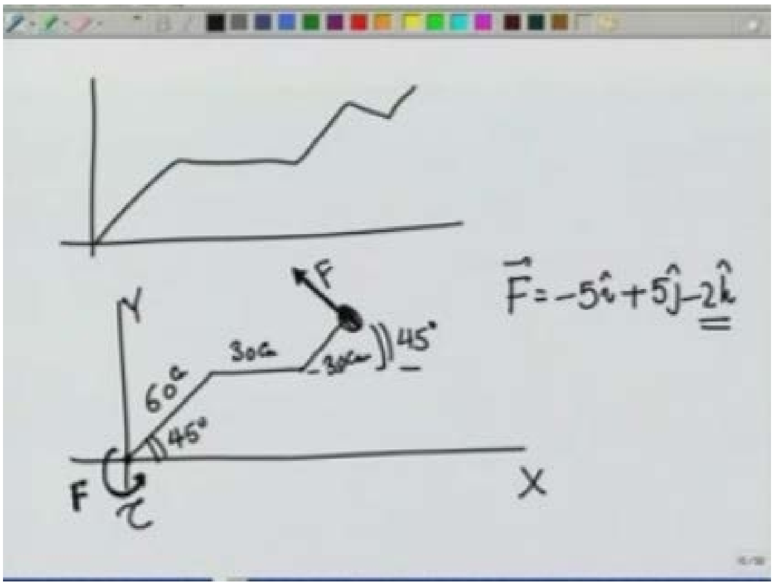

So, let us say if I take a handle in the xy plane of this shape the gear handle and this the head where the driver applies the force and changes gear. So, let us say he apply certain forces and I want to know what is the equivalent system How much moment does it generate at this point? And what force is transferred here? And that is what we do next.

So, let us take the length of this part to be 60 Centimeters, this part to be 30 Centimeters and this part also to be 30 Centimeters. Let this angle be 45 Degrees let, this angle also be 45 Degrees. And now, we say that the driver applies the force F which is equal to minus 5i plus 5j minus 2k. Something like this but, coming out it has a z component also or going into the boat because z component is negative. The force like this to change the gear. What is the equivalent torque and force at this point? So, we here in a way transferring the force parallel itself here and consequently we will indicate this force by an equivalent moment tau and a force F.

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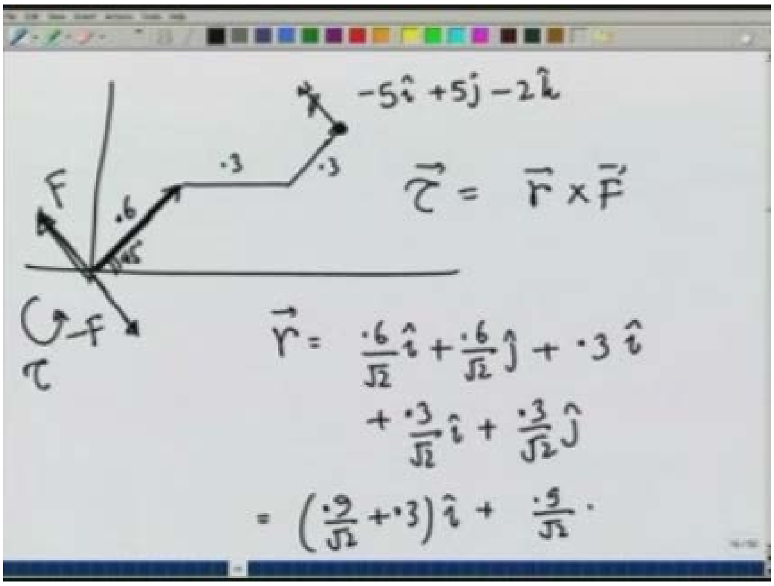

So, let me make the picture again here is the handle of the gear this is the here head this is 60 Centimeters or 0.6 Meters 45 Degrees this is 0.3 Meters and this is also 0 3 Meters. And the force out here it is minus 5i plus 5j minus 2k. The torque of the force is going to be r cross F equivalently. I can think of an equal opposite force being applied here and force equal to the original force being applied at the bottom. I have done nothing but, added 0 force on to the system.

So, now this minus F and the original force therefore create a couple here. Which is given by tau and the force is the original force here. Let us therefore, calculate this couple either I can calculate the perpendicular distance between the forces or I can straight away use the formula tau equals r cross F. Let us see, which at r is going to be in this case it is going to be equal to 0 6 over root 2i plus 0 6 over root 2j that is the vector from here the first part of the gear handle this vector plus 0 3i plus 0 3 over root 2i plus 0.3 over root 2j. And therefore, the total vector is 0 9 over root 2 plus 0 3i plus 0 9 over root 2j.

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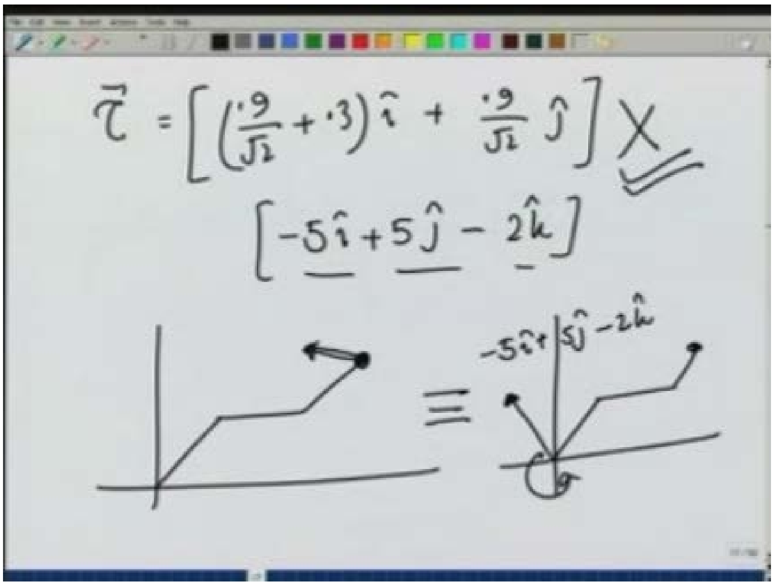

So, therefore the torque is going to be equal to 0 9 over root 2 plus 0 3i plus 0.9 over root 2j cross the force is minus 5i plus 5j minus 2k. I leave this is an exercise for you to calculate this torque. But, once you calculate this torque what you would find is, this gear handle on which this force was being applied this force system on this is equivalent to on the same. We handle as if, we are applying a torque here of the amount calculated here and a force the original force which is minus 5i plus 5j minus 2j.

So, this all of concludes an introduction to moments, couples and finding equivalent force and couple systems given a force about a particular point.

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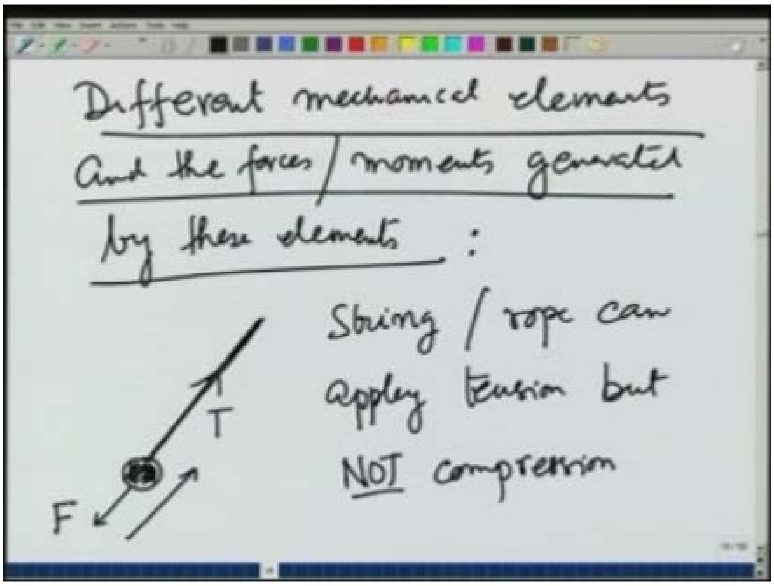

Next, we discuss different mechanical elements that I use in machines or a structures and the forces moments generated by these elements. Or a strategy would be I will take each element discuss about it and then solve a related example. The simplest of the elements is a string which can apply a tension suppose, I am pulling a ball or something tied at the end of the string by force F.

So, it is not moving then the string applies a tension in the opposite direction. But, remember a string or a rope can apply tension. But, not compression that is if I instead push the ball the other way the string would not be able to stop it.

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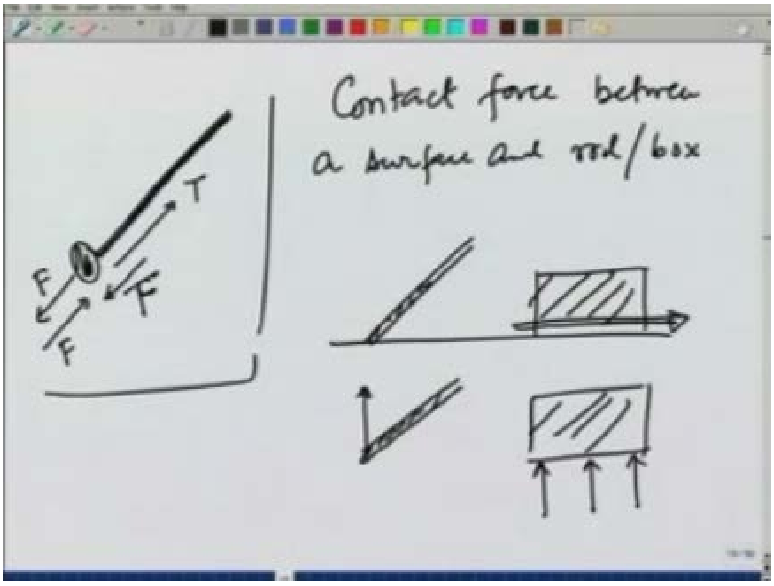

On the other hand if I have a bar made out of a material a rigid bar it can apply both a tension as well as a compressive force. So, if I have a ball at the end of it. If I pull it by force F it will apply tension T if the ball does not move if I push it in by force F it will apply the compressive force of the equal amount in the other direction. Next let us, discuss the contact force between a surface and say a rod or a box on it.

So, for example if there is a smooth surface and there is a rod here which is being pushed or whatever. And there is a box here the only force the only force a smooth surface can apply is perpendicular to itself. So therefore, it is capable of applying a force on this rod which is perpendicular to itself. Similarly, it is capable of applying a force on the box may be distributed may be at the same point which is perpendicular to the surface.

Why is it perpendicular? Image if it were not perpendicular what would happen. Then, this box because of the component parallel to the surface would start moving by itself that does not happen. And therefore, we conclude that a smooth surface applies the force perpendicular to itself.

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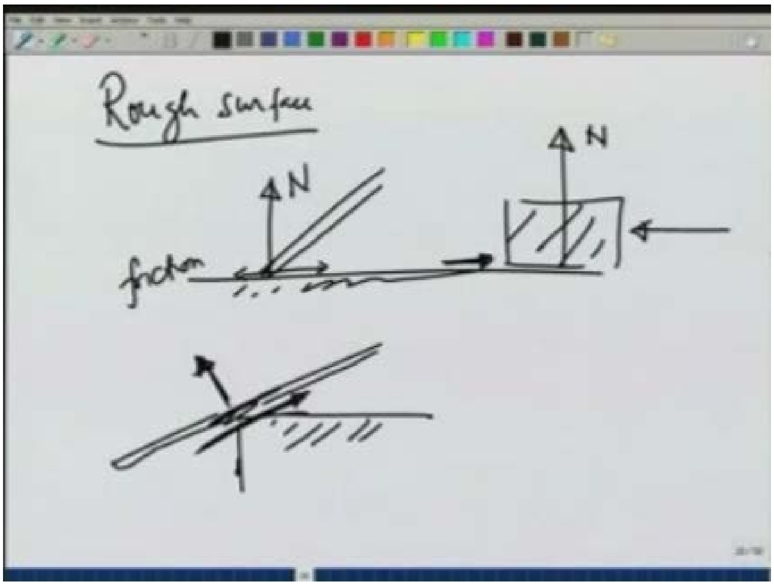

On the other hand if we take a rough surface. It can apply a force along a surface also opposite to the tendency in which opposite to the direction in which the object has a tendency to move. And therefore, this would be direction of frictional force due to the rough surface and of course, there is a normal force.

Similarly, if there is a box and if I am pushing it this way it will experience a normal force as well as a frictional force parallel to the surface. So, the smooth surface applies the force perpendicular to itself. Rough surface apply the force which also has a component parallel to the surface. By similar logic if I have a plunge or a rod on a smooth on an edge.

Then, the force on this plunge is perpendicular to the surface of the plunge due to the edge. Of course, I am the direction in this side would not be there. The only direction in which the edge can apply a force on to the plunge is in this direction. If on the other hand, there is some roughness then there could be a force frictional force in this direction also, recall the example that we did earlier where we had a break.

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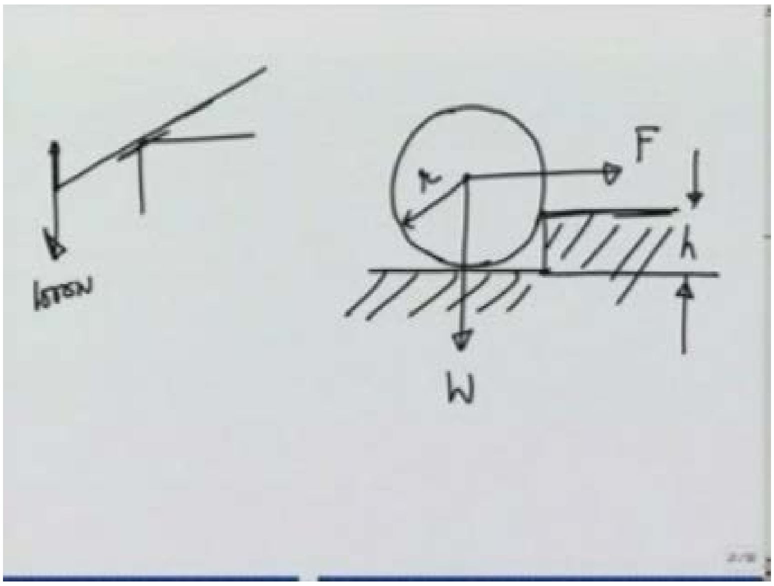

On which I had a rod an outstand to lift a weight like this which applied a force downwards of 1000 Newton's here. We realize that without the roughness here that rod would tend to slip. Let me, now do one example of this problem let us say, I want to pull a roller this is a very standard problem. Over, a step like this the height of the step is h and I am applying the force F in this direction parallel to this and the weight of the roller is W the radius of the roller is r. I want to know what force should I apply in order to take this roller over this step. Let us see, what all can we do?

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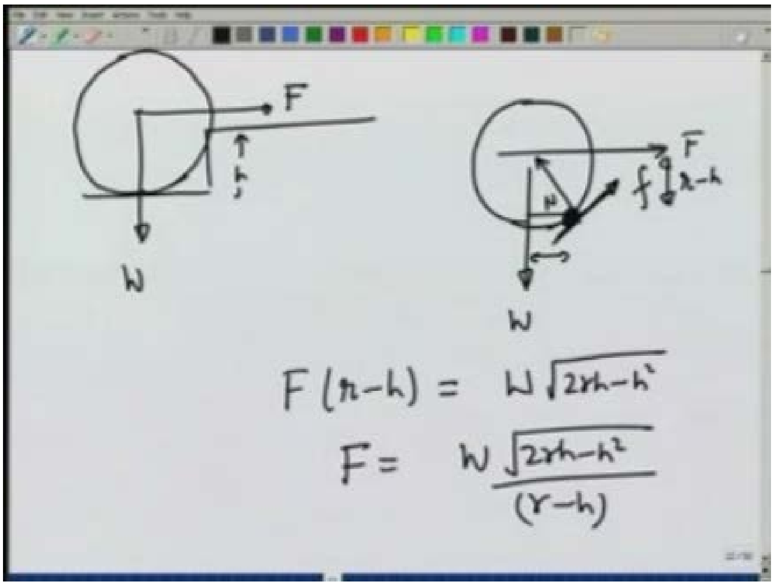

So, let me make this again I have this roller. On which I am applying the force at the centre to the right this height is h is being pull down by W. Now, the possible forces on the roller if the corner is rough is of force like this, frictional force and a force towards the centre the normal force. Then, the force that we are applying F and the weight W. To find F it is very convenient to take this point as the origin and balance torque about it that would straight way give in order for equilibrium F time's r minus h.

Because, this distance is r minus h is going to be equal to W times this distance which we workout is going to come out be 2 rh minus h square. And therefore, the force that I apply should be equal to W Times Square root of 2 rh minus h square over r minus h. That should be enough to take it over the step. What about these forces? The force F and the force N. Let us, calculate those also so, you see now in this problem I am applying the torque equation first and the forces equation later.

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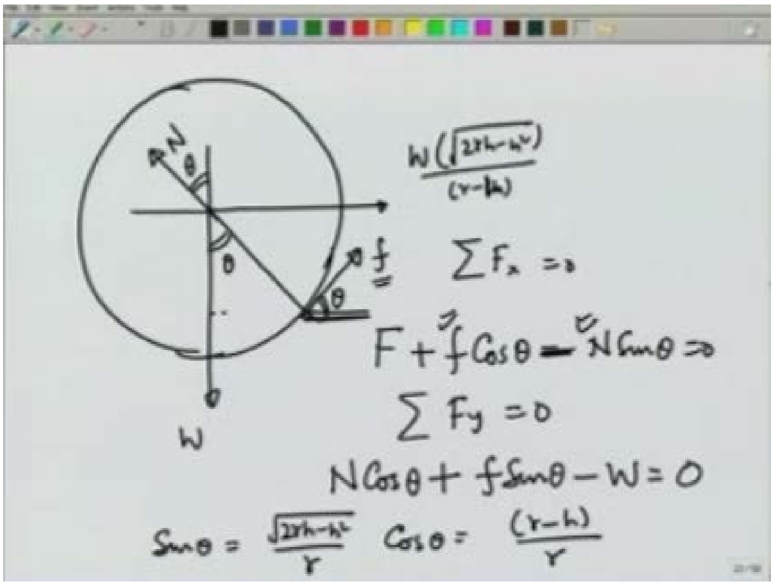

Let me, make this big and now we see at this force is W Times Square root of 2 rh minus h square over r minus h this forces W. This force is N and there is a force f like this if I take summation over Fx is equal to 0. Then, the horizontal component of the force f frictional force should balance the horizontal force otherwise applied. So, I find that F that is the force that we are applying plus f.

Let us say, this angle is theta cosine of theta should be equal to if this angle is theta and this angle would also be theta. Because, this is perpendicular to F and this line is perpendicular to this line. So, it will be minus N sin theta it is equal to 0. And similarly, for the vertical forces summation fy is equal to 0 would give me N cosine of theta plus f sin of theta minus W is equal to 0. These two equations are enough to determine smaller the frictional force and the normal reaction N.

Here so, in this angle is theta you can see that this angle is also theta. And therefore, sine theta is nothing but, the square root of 2 rh minus h square over r and cosine theta is nothing but, r minus h over r. If we substitute these values in the equations we find N is equal to W r over r minus h and f is equal to 0.

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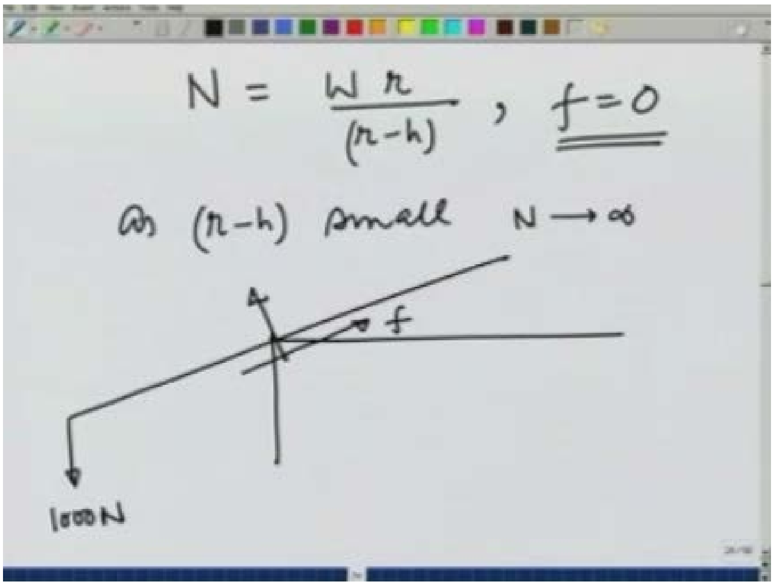

So, this is a very special case where to take the roller over the step you do not really need any frictional force on the edge. Notice that as r minus h becomes a small n goes up. So therefore, the normal reaction keeps on increasing as h becomes larger and larger and larger. Compare this with the case that I discuss while ago and also worked out in detail in the previous lecture where we had a rod lifting a 1000 Newton weight. In that case in order that the rod not slip over the edge we had to apply or we required a frictional force on the edge.

So, what we learn is that a rod or a plank on an edge can apply normal force in the case of smooth a surfaces and a normal force and a frictional force when the edges and surface are rough. Next, we consider an element which is a pin or the hinge same thing. That is if I have an element a rod or a plank and it is free to rotate about this point it is hinged to here.

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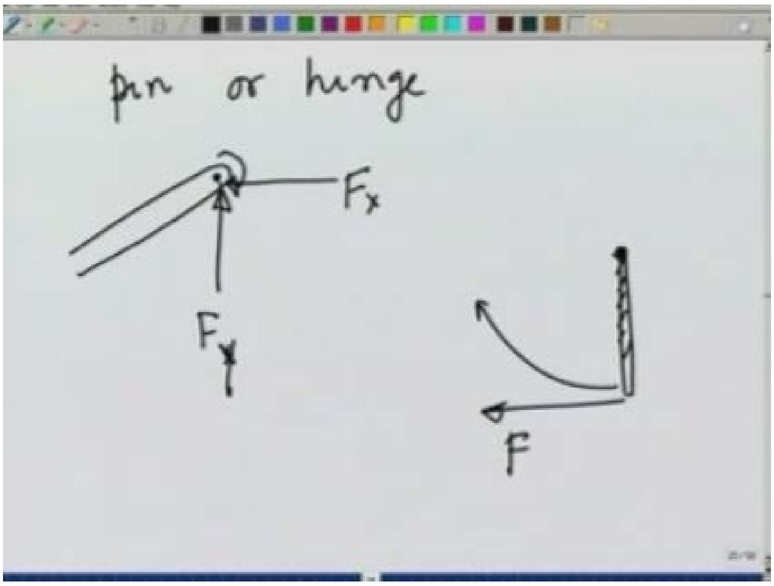

In that case the hinge cannot apply any torque, but applies a vertical force and a horizontal force Fy and Fx. These are the only two forces that it can apply nothing else. So, let us see an example of this you have all traveled in trains and sometimes when a berth is in its vertical position you apply a force F like this in order to pull it up. And this is hinged at this point. So, the problem we want to solve is suppose you pull this berth out.

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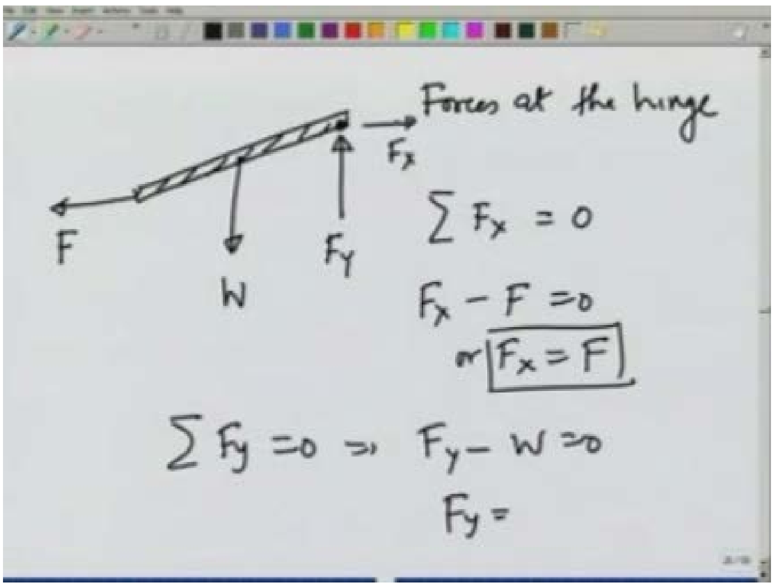

And you are applying a constant horizontal force F like this. The weight of the berth is W and it is hinged here. I want to know the forces at the hinge as I said this now, the hinge is capable of applying a vertical force and a horizontal force Fy the vertical force and Fx the horizontal force. Then, summation Fx is equal to 0 gives me the horizontal force and that gives me Fx minus F is equal to 0 or Fx equals F. Similarly, summation Fy is equal to 0 gives me Fy minus W is equal to 0 or Fy is equal to W. Next, we want to calculate given this force F and given this weight W what is the angle theta that the berth makes from the horizontal. Let me, make this picture again.

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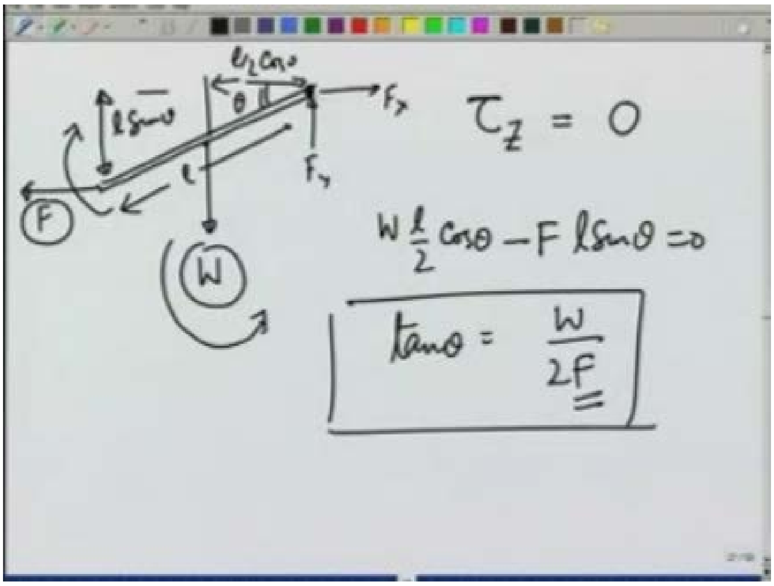

So, this is the birth you pull it out with force F this is being pull down by its own weight W to applying force Fy and Fx are being applied by the hinge the length of the rod is l. There are torques when I take torque about this point being generated by weight W and the force that I am pulling with. If I take torque about z axis should be 0. Then, the weight is giving a torque in this direction counter clockwise is going to be positive. And F is giving a torque in this direction which is negative this gives, let us calculate distances first.

So, this distance is going to be l over 2 this angle is theta cosine of theta. And this distance is going to be l sin of theta and therefore, when I put tau z equal to 0 I get W l. Over 2 cosine of theta minus Fl sin of theta is equal to 0 and that gives tangent theta is equal to W over 2 F. You notice, larger the force that you apply smaller the angular that you experience when you do something like this, you pull the berth out it goes higher and higher and higher. So, this is an example of solving a simple problem using hinge forces.

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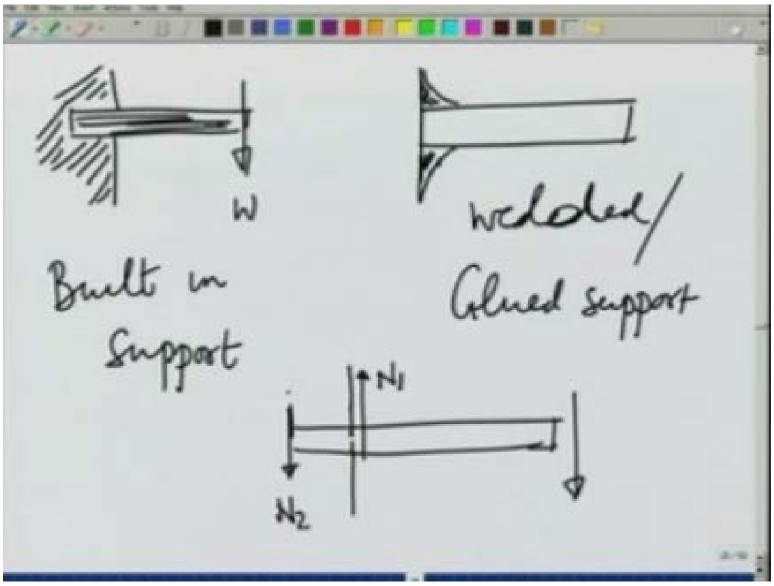

Next, we look at built in supports that is suppose, there is a support or a beam which is inserted in a wall and is like this. And I apply the load here in any direction or a support which is glued to a wall. Suppose, I will glue it here glue or weld. So, welded or glued support and this is built in support what all are these capable of. So to understand this, let us say I take this built in support first and apply load here may be hang something.

Then, you know this point tends to go down and this point will tend to move up. As the support pushes the wall down this is going to be a force. Let us say, N1 the normal reaction of the wall on the support and similarly this end is being pushed up so, this would experience a force N2. Let us, go to the next page and see. So, what we did we looking at this built in support. And when, I apply a force this direction.

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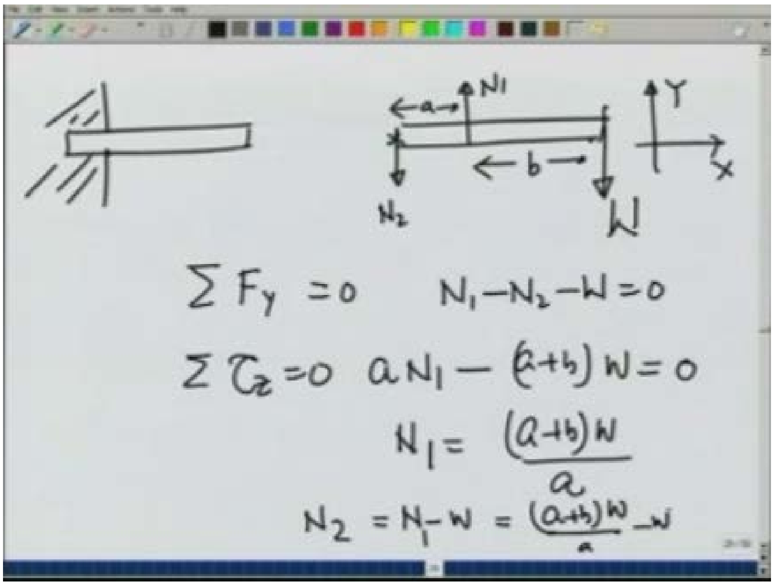

Let us say, W at this point there is a normal reaction N1 and at this point there is the normal reaction going in this direction N2. Let us say, this distance is b and this distance is a. Then, since there is no force in x direction I need not worry about it I am taking x direction like this and y direction like this. Summation over Fy is equal to 0 gives me, N1 minus N2 minus W is equal to 0. And summation tau z about the z axis equal to zero.

Let us say, I take it about this point all the once the force as 0 it does not really matter it gives me, a times N1 minus a plus b times W is equal to 0 or N1 is equal to a plus b times W over a. And similarly, N2 would then come out to be N1 minus W or this is equal to a plus b W over a minus W which is equal to b W over a. So, what we find is was the built in support

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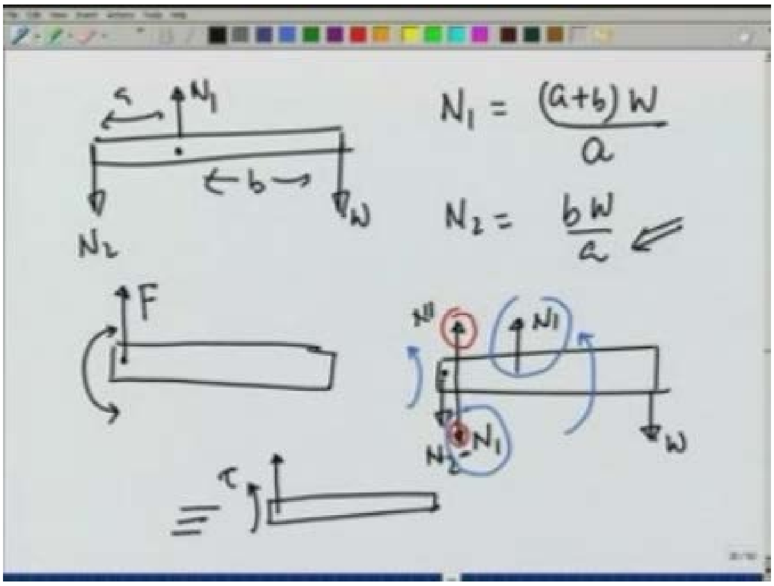

N1, N2 W we have N1 this is b this is a is equal to a plus b times W over a and N2 is equal to b W over a. I could have got in this answer directly, if I took the torque about this point. But the point I am trying to make now is going to be slightly different. I could think of this whole thing this built in support as if, it is applying a torque at this point at the end in 1 direction or the other and a force F. And that is how I would represent a built in support.

Let us, understand how this can happen. So, once I have determined N1 and N2 this is W I can add the 0 force at this point and I choose this 0 force in a particular way. I add N1 and minus N1 at this point. Now, this minus N1 let me, use a different color minus N1 along with this N1 gives a couple a couple trying to turn the whole thing counter clockwise.

So, this gives a couple at this point in this direction. And this force N1 and N2 added together give me a force. So, this whole thing is equivalent to a couple a moment torque here and a force N1 minus N2 here which obviously, is going to be equal to W. So, what we say for a built in support system is that this is capable of giving a torque and a force at this point.

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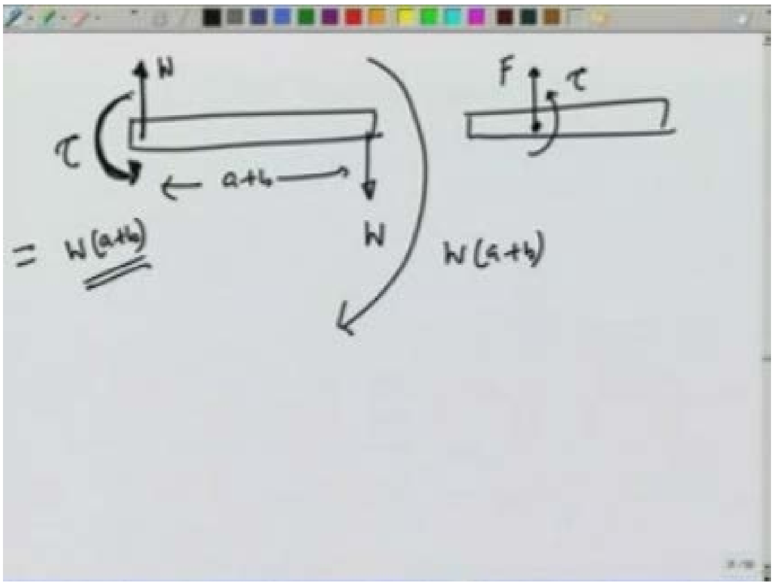

Of course, I could have done the entire analysis about point b is point near the wall where it enters the wall I would still say, by the similar analysis that this this capable of giving a torque its value would be different. Because, now being doing things about this point and force here. So, I can think of a built in support system as providing a torque and a force.

Of course, the moment I apply a weight here this force has to be equal to this and therefore, weight it has to be equal to W the length is a plus b. And therefore, this forms a couple which gives a torque in this direction as W a time plus b. And therefore, the torque generated at this point to counter this torque is also going to be equal to W times a plus b.

So, think of a built in support system as something that can generate a torque as well as the force. You notice, that with a plus b increasing if a plus b is large this torque is going to larger and larger and larger. It is actually better understood if we go back to this slide.

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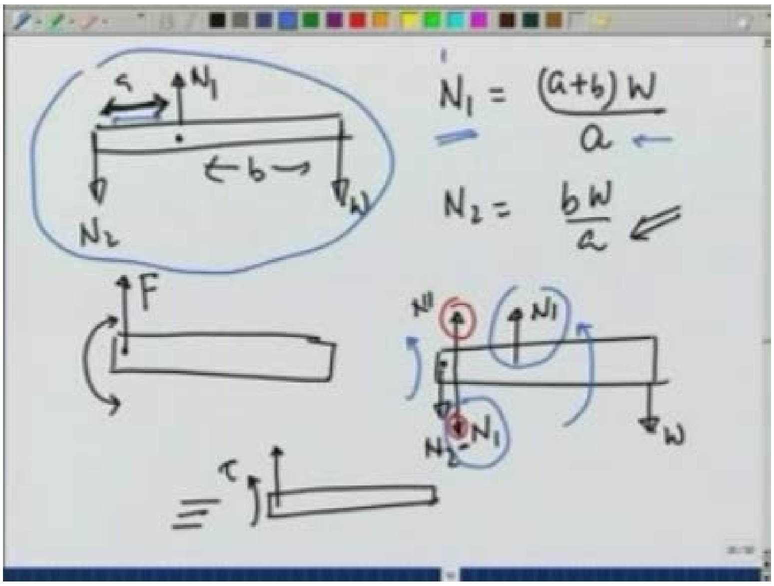

So, see if a is large if a is larger I am talking about this picture. If a is large then, N1 provides a larger and larger and larger torque. And therefore, with large a I need less N1 at this point and therefore, if you want to have a very stable support push it really deep into the wall. Let us, see now a similar support which is not into the wall which is not built in, but it is welded at the corners.

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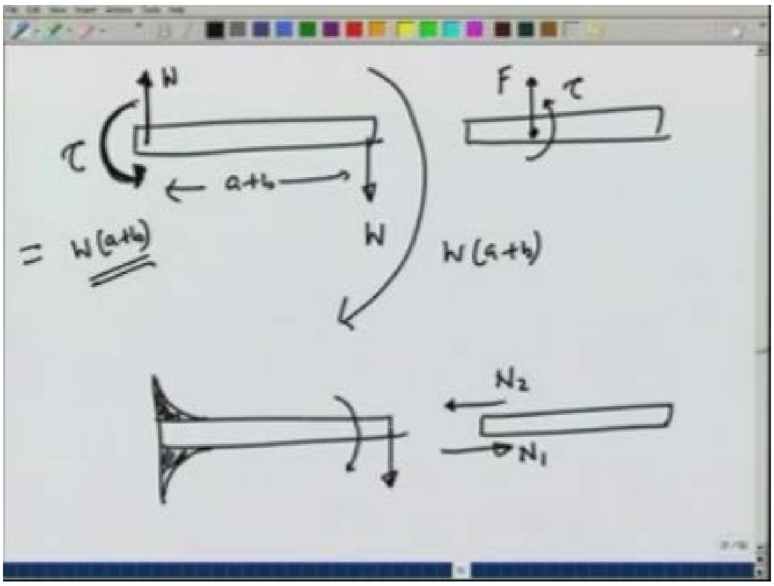

So, I apply load here. Let us, see what will happen as this load is applied you will see that this has a tendency to turn like this. And therefore, there will be a force generated in this direction let us call this N1 and there will be a force generated in this direction let us call it N2 using the analysis.

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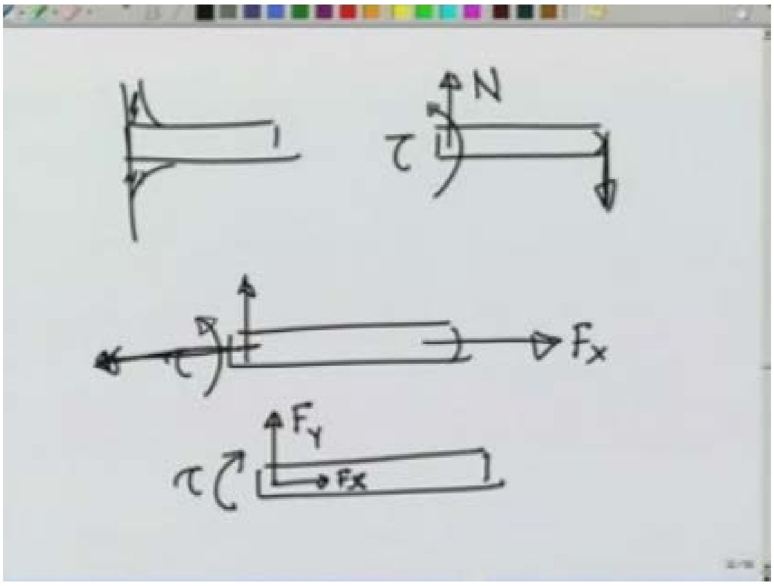

Similar, to what I did just now for built in support system I can again show this to be equivalent to giving a torque and a net force normal reaction to this load. So, both a built in support system and a glued or welded system are capable of generating a counter torque and a force and this is how I am going to represent. We have not considered x component of force so far you know; obviously, if I pull this thing by a force Fx the built in system. Or the glued system also generates a force in the opposite direction because, the thing does not come out.

So, therefore, the complete picture a built in support system or a welded system is capable of generating a torque, a vertical force and a horizontal force. This is how we represent a built in or glued system. I will do one example of this kind of element. That is a built in support system which can provide a torque as well as the vertical force and a horizontal force in the next lecture.

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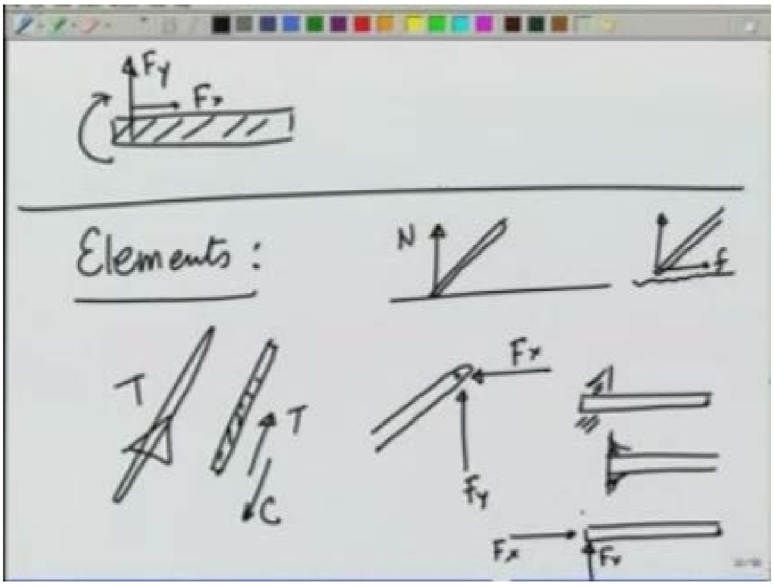

But let us see, what all did we learnt today in this lecture. We first completed our analysis or discussion or of moments of force. And then, we looked at elements various engineering elements and what kind of forces they can apply? We look at a string and saw that it can generate a tension we looked at the rigid rod it can generate a tension as well as compressive force.

Then, we looked at a smooth surface where we saw that it can generate only a normal force and a rough surface which I am going to show like this which can generate a normal force as well as a frictional force along the surface. Then, we looked at pin or hinge joints and this can create a force in x direction as well as in y direction. And finally, we looked at built in support systems or welded or glued support systems and. So, that these are capable of generating a vertical, a horizontal force as well as a couple moment.