Advanced Topics in the Science and Technology of Concrete
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Closed-Loop Testing Part 2

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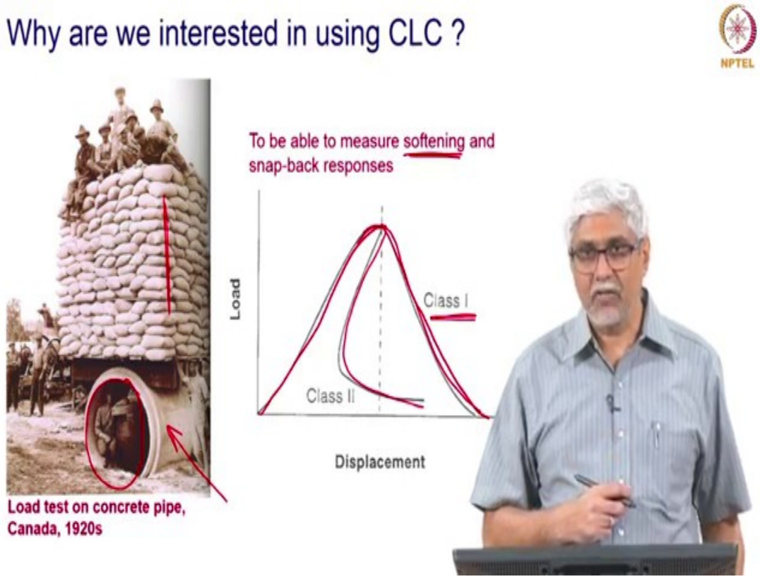

Now why do we have to go to all these lengths? Traditionally for long back even now also we do some load testing like shown above, which you can see in the image from the 1920s, this is how they tested a concrete pipe , so you see there, that the concrete pipe is being tested and weight it is applied. You keep on applying weight with sandbags, until the load carrying capacity is reached , then you know that it is safe and if it broke what would happen? The pipe gets crushed and incidentally, you see one person sitting inside, so the story goes that this was a person who designed this pipe and he was so confident, he said that I will sit inside, I do not know how many of the modern engineers would do this but this person had the courage to do it.

Anyway, that is the story but this would be a traditional load control testing, where you keep on adding load you only want to know what is the maximum load the pipe in this case can take . However we also want to know how this pipe or any material fails, when does it start filling? How does a crack propagate? So we want to be able to get a response not only up to peak load but also the remaining part, that is called softening as opposed to hardening that we see in metals, where there is yield and then after yield the stress goes up that is called hardening and the opposite of that is softening when you have a softening of this type , this is what is called a class I response.

A class II responses is where you have snapback because of some elastic component in the specimen or outside the specimen which is causing this, I will show you some examples of how a specimen can also give you class II type of response, both these cases it happens because the material is softening, like concrete, rocks, ceramics these are materials which are softening materials.

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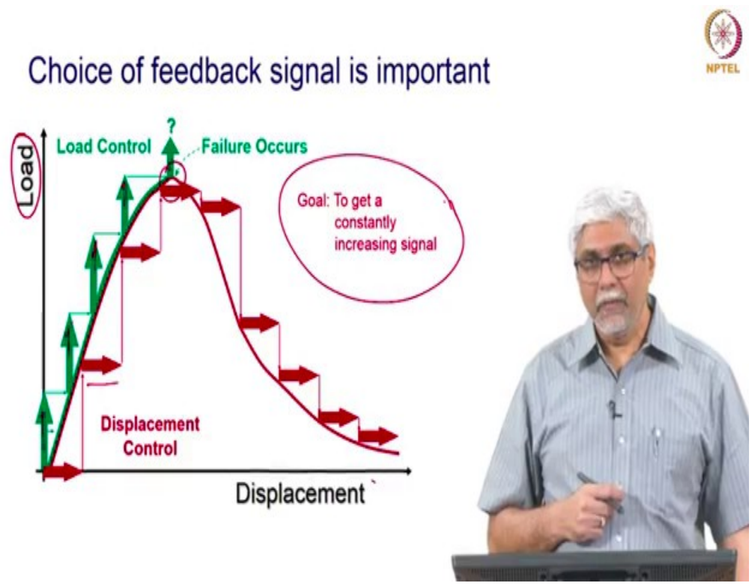

Above is another way of looking at the difference between load control and what it can do or displacement control suppose you have a specimen which is softening and it would give a load displacement curve like that, if you were going to do load control, the load is always trying to increase, the machine is increasing load, so at this point, the specimen cannot take more load and therefore it fails but if you were to do a displacement control test, only displacement is increasing, so at this point the displacement continues to increase and the reaction is the load which is also measured and you will get this complete curve, so the objective always is to do a test such that you get some constantly increasing signal, so the decision on which the constantly increasing signal depends is on your understanding of the test and I will show you the examples of how we can do different types of test by this understanding.

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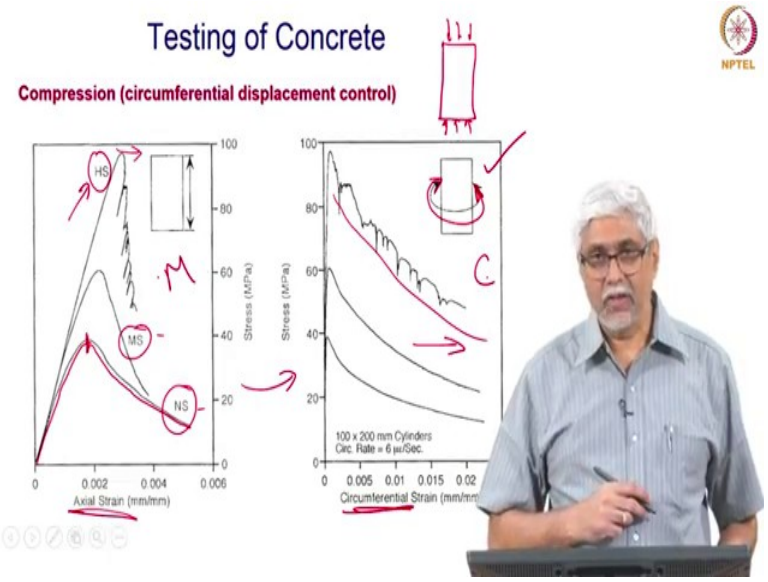

Suppose we want to do a compression test, say a cylinder or a prism and we want to do a uniaxial compression test, all of us have seen red that beyond a certain load the specimen just fails, in above image you can see graphs of the behaviour even after the peak, there is lower strength concrete, medium strength concrete and high strength concrete, that is about 20 MPa, this is a 40 MPa and this is 100 MPa respectively. You find that in all the cases the specimen has an elastic range, a non-linear reaches a peak and then continues to drop it, that is the softening response that we want to capture, this is what is needed for non-linear analyses of a reinforce concrete structure.

If we do load control, we will not get anything beyond the peak, But we need to capture that, however we can see that when the concrete is very brittle, the displacement does not change a lot, the axial strain does not change a lot, so if we were going to use just the displacement or the axial strain for testing or the controlling, we may not get the response of high-strength concrete, so we have to look for something else that is always increasing and the answer is the circumferential displacement , so as concrete is compressed, it dilates, it expands and this expansion is always increasing after the first cracking, Earlier we were looking at axial strain and so if you see the circumferential stain of same specimens, we find that without any drop the specimen is always such that the circumferential strain is increasing.

So if we were going to control the test this way, then you will get a stable response and this you can measure, it is not that when you do this you do not have the axial strain which is important, you can measure axial strain but control with circumferential strain, so that is what we generally do.

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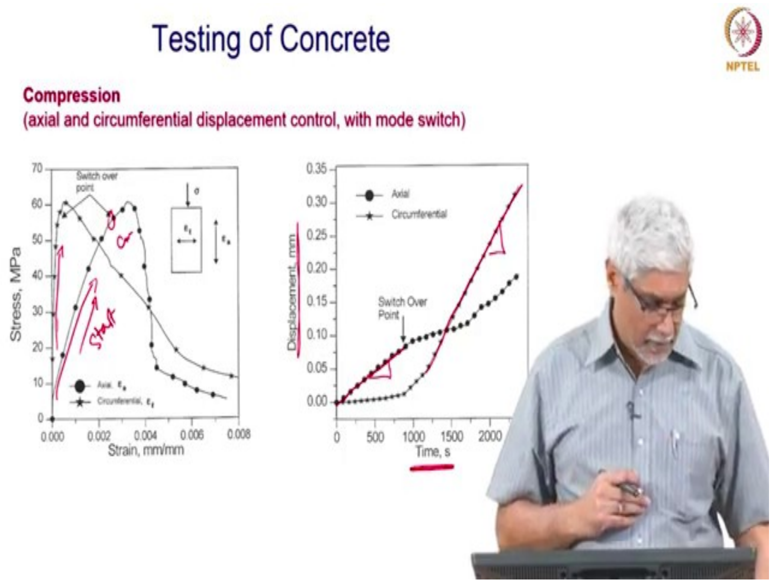

We can also switch control for example, above, we have the axial stress strain curve verses circumferential strain, what we find is initially the circumferential strain does not increase much, so what you would do is start the test with axial control and switched to circumferential later , at switch over point is where it is switched because you want to start of the test such that you have some sensible parameter, sensitive parameter, so you start of the test with axial or you can even do load control and then switched to the circumferential when you want it.

So this is the displacement versus time , so what was done is it was decided that the axial strain would keep increasing in a certain rate, it reaches a certain point and then it is switches to the circumferential strain which then increases linearly, so the control has being switched from a linear increase in axial strain until a certain point and then switched to the circumferential strain, so good control system should allow us to switch from one parameter to the other and in our labs generally we would start of a test with load control and then switched to some strain control could be axial then circumferential depending on the test.

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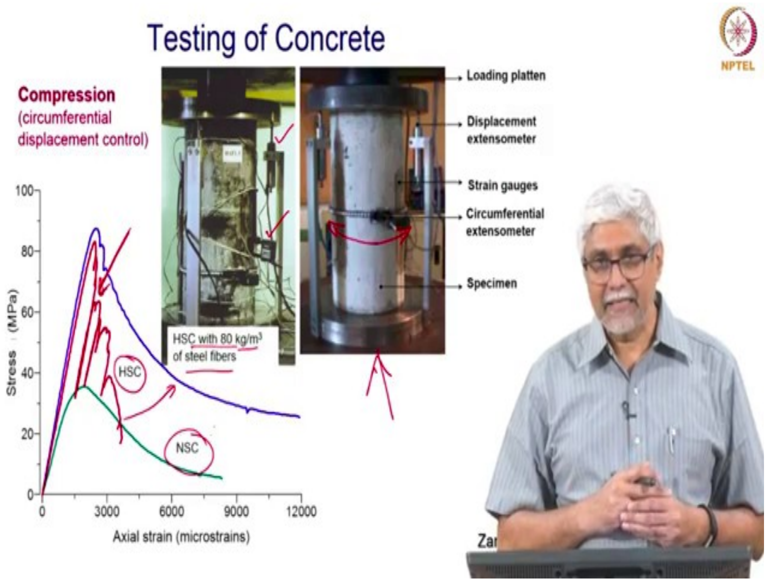

So these are some test by our group which shows the normal concrete, high strain concrete and fiber reinforce concrete behaviour and you can see that we have been to capture the high strain concrete behaviour, even though there is a lot of snapback, I talked about snapback earlier, so you see that there is when we do very high strain concrete, the concrete is so brittle that there is no constant increase of deformation, after sometime the specimen just starts to break apart but we still want to capture this because for the structural analyses we need to know how this specimen or how this concrete is going to fail and here we see also an advantage of understanding this.

We have shown for example that the same concrete can change its post peak behaviour significantly by adding fibers, so in above image, that is the same concrete; the blue line is the same as the red line but blue one has 80 kg of steel fibres, whereas the red one does not. so, by measuring this we can also engineer the concrete, we can modify the concrete so that it does not behave in such a brittle manner and for this we have to measure it and the only way to measure it is to do a test of a specimen,

Where we have a chain that is placed around the specimen which is measuring the circumferential strain and in addition, we have to have measuring devices for the axial strain. we want the axial strain but to get the axial strain we should also measure and control the circumferential strain, so it is a very tricky test but once you have a good system and somebody who is knowledgeable, we can easily get these types of responses and capture them.

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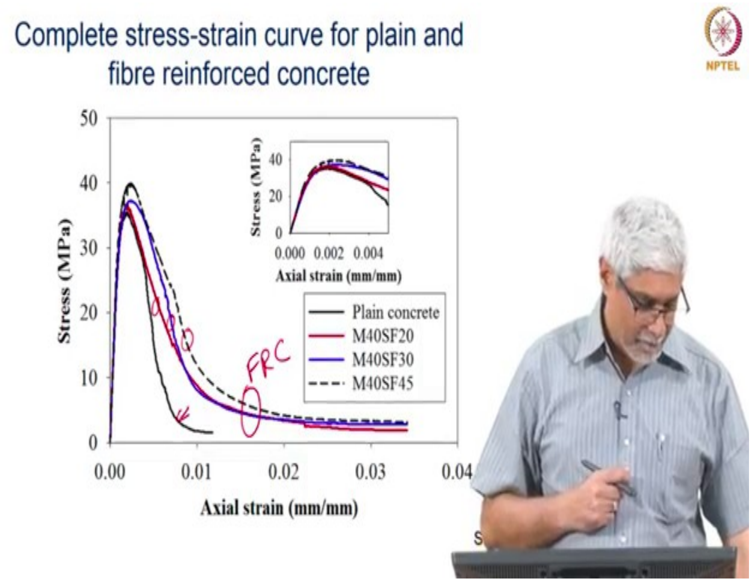

Above Stress-strain curve is by one of our students Steffie, where she is looking at the responses of different types of concrete, this is plain concrete and these are fiber reinforced concretes and she is looking at what is the effect of adding a little bit of fibers to see how the deformation changes, with 20 KG, 30KGand 45 KG of fibres, so this tells us how the post peak behaviour or how the failure behaviour of the specimen is changing or the concrete is changing as we add fibres, so this type of test gives us that explanation.

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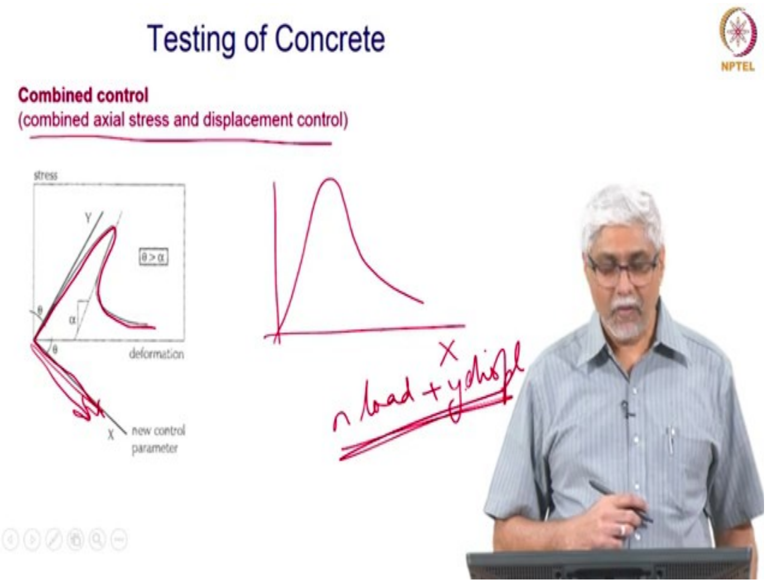

, so I talked about the possibility of controlling a test by using displacement, sometimes we can combine also for example, in above there is stress displacement curve, there are people who have combined axial stress and displacement to control, by inventing a new parameter that is used for control ,so that could be made into a curve, where there is the new control parameter X, which could be a combination of N times the load plus Y times the displacement , so new parameter which does not have any physical meaning is invented to run the test such that parameter given by the new one is always increasing.

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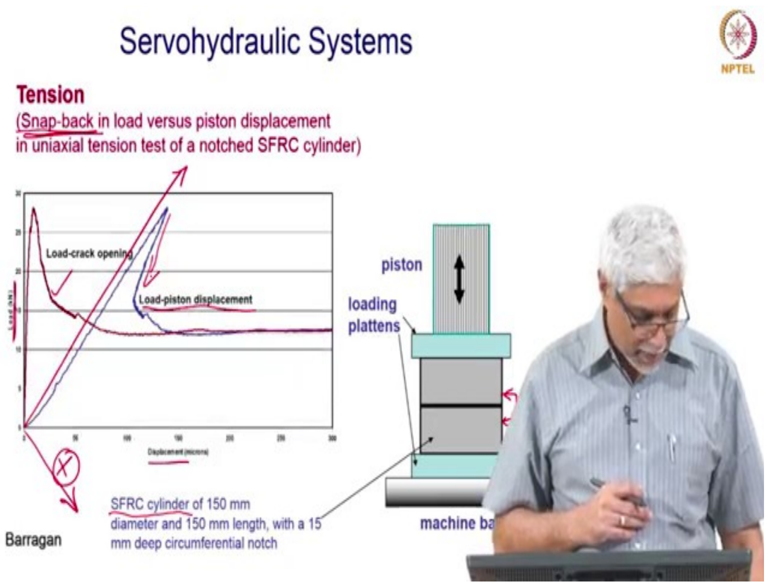

an example of this can be seen here, so in tension test above, where we have a steel fibre reinforced concrete cylinder with a notch around it and we are trying to do a tension test, we have glued it on to two places and this is being pulled apart, so there are two ways to capture the displacement of this, either we put a transducer, which is telling us exactly how the crack is opening and that will be the control variable, then I would get this red line behaviour shown in above image, which is as expected or as I know the displacement direction of the load piston, I have to invent a set of parameters which show the axis in certain way .

So I control the variable X, which has a component of displacement and a component of load and I tell the machine to keep increasing this X in a certain way and I will get behaviour that is now stable for the test to run and then I can capture whatever response it is, either I know exactly what is always going to increase and I measure that or I look for a combination of parameters which is always going to increase, so these are things that again require a little bit of experience and trial an error to figure out how they should be done and this is basically important when you have a behaviour called snapback.

It Snapback is this, when the displacement decreases and for many years until the 80s people never believe this was true, people thought that this is impossible, this is just that some people are doing the test wrong and that is what is happening but what all I am showing you are real test data where this is happening and there was, there is a professor Surendra Shah who spend a lot of time on this and you will hear him in another lecture of this course talking about other work that he has done.

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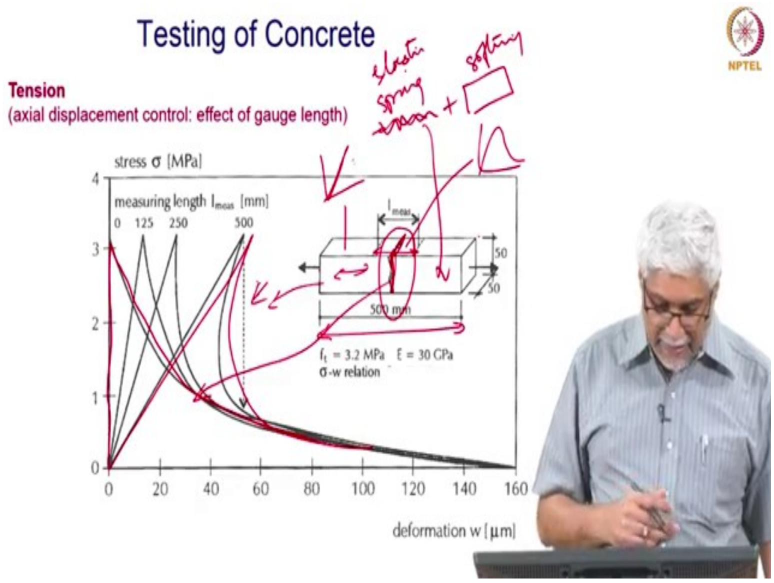

Another time when you can see snapback is when you use a very long specimen, suppose you do a tension test on a very long specimen say of concrete or rock, what we find is after a certain stress, there will be one crack which will open, so all the deformation is happening only at this crack, the rest is only elastic , so going back to the diagram I showed you of a spring plus a concrete specimen that is what happening. In above image there is part of concrete acting as an elastic spring and that is the softening element.

So the larger the specimen, longer the specimen more is the elastic part, In above deformation graph, it shows the response of the crack, if I am measuring the whole thing, then adding on a elastic part, I get snapback, there is a lot of snapback means what, snapback means that energy is coming back from the elastic part when we are unloading .

As shown in above image, in your load displacement, first part is going linearly and the butt sawed part is doing the softening, so when you add, if first part dominates you get snapback type behaviour as marked in above image when you have a long elastic part or in the same specimen if you are measuring very far away from the crack on including a lot of elastic part, then you have softening coming in and the test is unstable, so that is we have to figure out where we have to put the it transducer. And in most tests nowadays we put a notch, so that we know where the crack is going to start and that is where will put the transducer, so this is an example of snapback.

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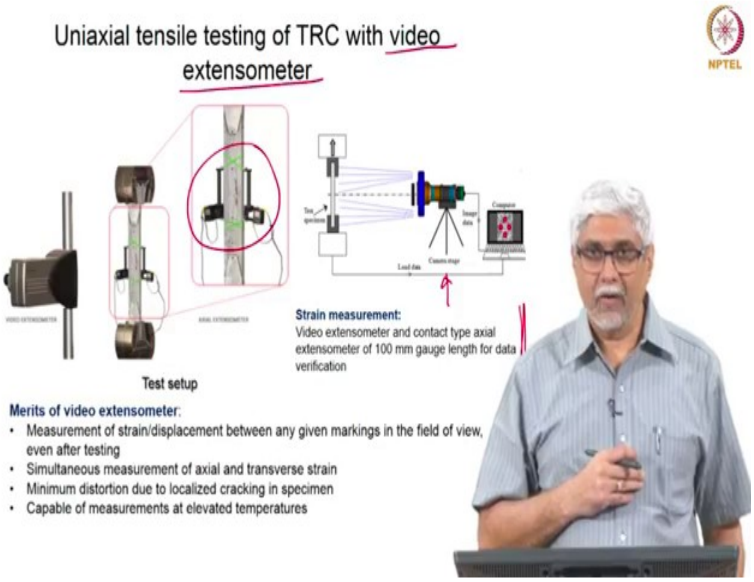

Now these are test of one of our research scholar Sachin Paul, he will show you in a video of how these test are done, so this is textile reinforced concrete, so it is very ductile composite where you have embedded glass fibres in a cementitious mortar and the possibility of the test that Sachin is running is that we can use video extensometer, until now we have talked about transducer, extensometer which are put on the specimen but nowadays we have this sophisticated video extensometers, which through a video camera is measuring tiny points on the specimen and calculating strains and it is possible that you can use these strains to control the test and in addition you can also have these axial extensometers which are looking at how the cracks are, so these are some of the merits or more details of these video extensometers which are now available so that without putting something on the specimen but by looking at the image or a series of image or how the images changing you can figure out what the strains are and use it for control.

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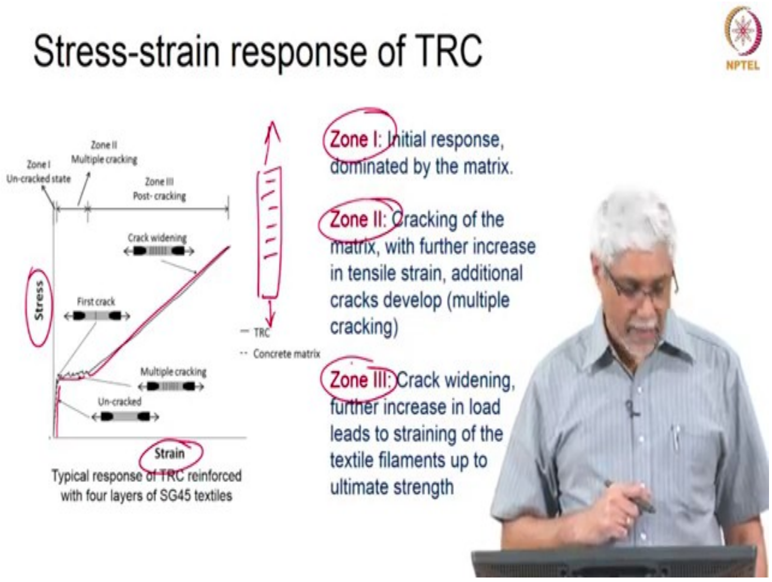

And with something like that you could get a response which is shown here of stress versus strain in a textile reinforced panel which is subjected to tension and here you will see that there is an elastic part, then there are cracks, and the crack start opening more and more, so this will tell us the different zones of behaviour for which he is doing his work , so Sachin, you will see a video of Sachin explaining test on TRC later on.

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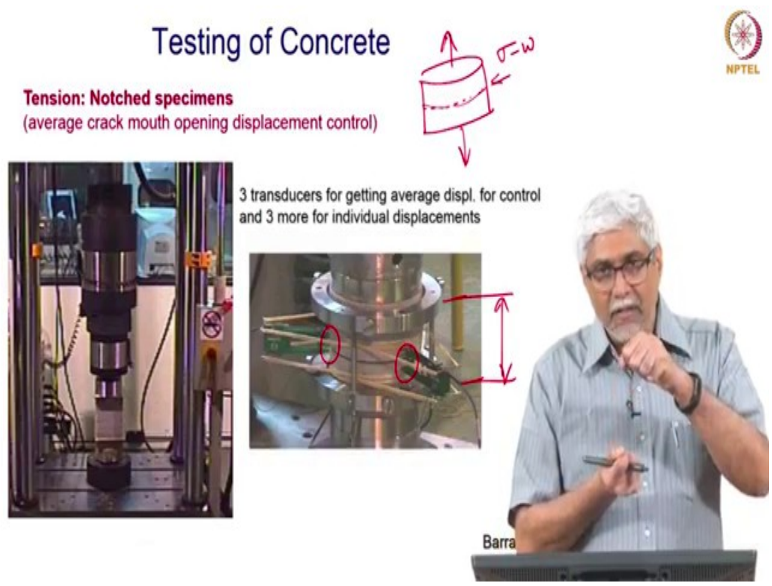

As I told you we do a lot of test on notched specimen, the idea of using notched specimen, In above image, you will not see clearly what the specimen is but basically it is a cylinder with a notch and we are applying tension because we want to know what is the stress crack opening behaviour, what is often called the σ-w behaviour, so we put a notch because we know that the crack will only open there we can then control it, so you see here that this is the specimen very heavily instrumented, we have this system measuring the axial displacement and then you have here these gadgets measuring the crack opening , so you can see, we can apply load and see how the crack is opening and figure out what is the stress crack with behaviour.

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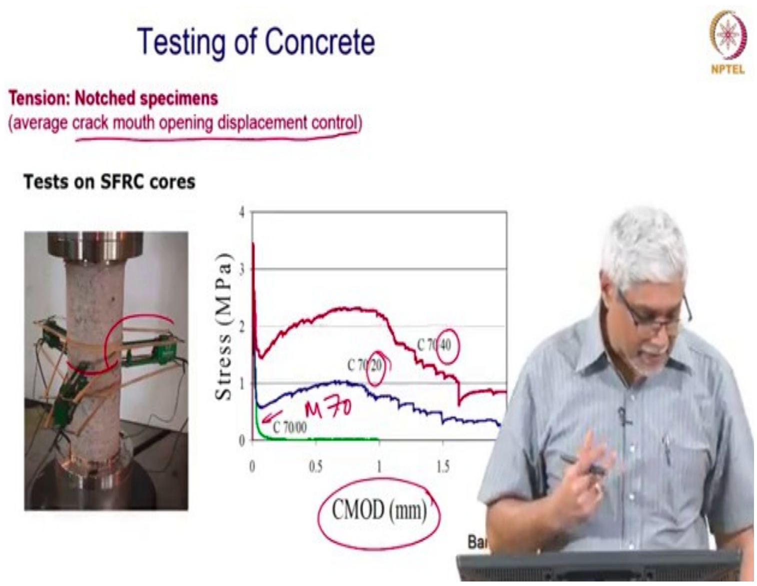

And you can get a behaviour like above, those are test on cores, you can see how the specimen, and you can see that there are three extensometers around the notch and the averages plotted here as the crack mouth opening displace CMOD is the crack of mouth opening displacement, so we control the test such that the crack mouth opening displacement is always increasing and you can see that something that is plain concrete gives a green curve, this green curve which almost shows no stress or no load carrying capacity after the first crack it just fails, you are trying to open this and suddenly it breaks but something with about 20 kg of fibres will have some load carrying capacity, 40 kgs of fibers and this is a like an M70 concrete .

So even a very brittle concrete with has some fibres, when the crack opens the cracks bridge, the cracks are bridged by the fibres and the crack does not open and that is what you can see by doing this test, this is very difficult test again but it is possible.

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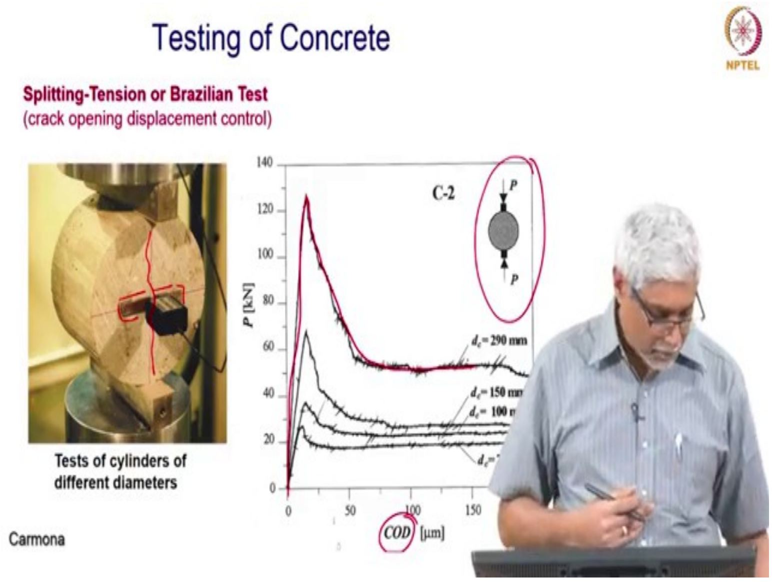

And even more complicated test and very challenging is to do the Brazilian splitting test, all of us who would have heard about this splitting test would have studied about the splitting test, where we take a cylinder and be apply diametric compression and calculate the strength, now what we wanted to do is see if we can control this test such that there is no sudden failure, anyone who has done this test knows that at a certain point the specimen just breaks, right and it get two halfs but so the challenge was to see if we can run this test without the sudden failure and we achieved it by putting two steel plates.

We know that the crack is going to run towards it because that is how it has to fill, so we put the two steel plates and put a clip gauge across it and try to control the test that way and you see how the behaviour is, we are controlling COD and there are different sizes of specimens, you see that you get the elastic behaviour, then the crack starts and the crack is slowly opening, we are losing load carrying capacity and then flats out, so we could so that even in this test you could obtain a stable behaviour and then use this to understand how a crack is propagating under diametric compression.

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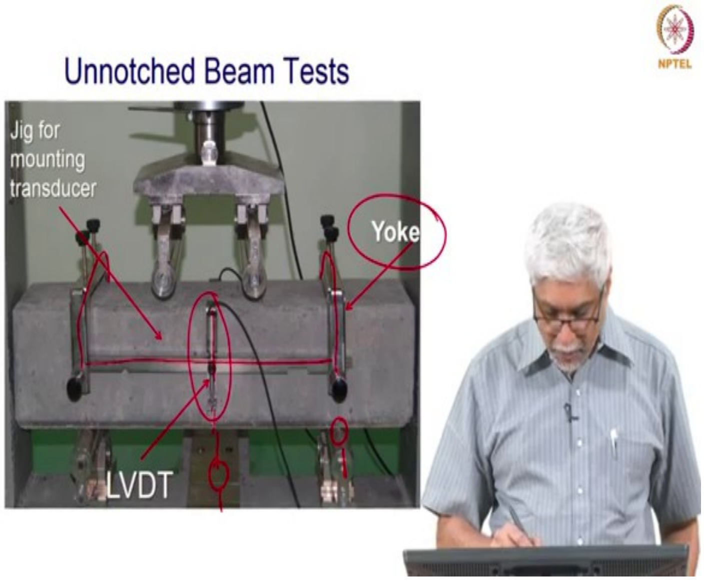

The same thing can be extended to unnotched beam test, so the beam test where you have to use for the modulus of a rupture and also you want see how the specimen breaks and here you see a specimen that is instrumented with what we called a Yoke, which is like a frame that is holding the extensometer so that we can get the displacement, so it is very important that we get displacements right, often what is done is there will be a dial gauge put between the bottom of the specimen at the bottom of the testing machine but this means that what you see as displacement will include many other displacements which are not just the displacement of the beam.

For example the crushing and the displacement of the supports, all this will show up as displacement, so what we do here is we have the frame which is clipped on to either side and then you have the bar here and on this bar the LVDT is attach and it is resting on something that is glued on to the concrete, so we get the true displacement.

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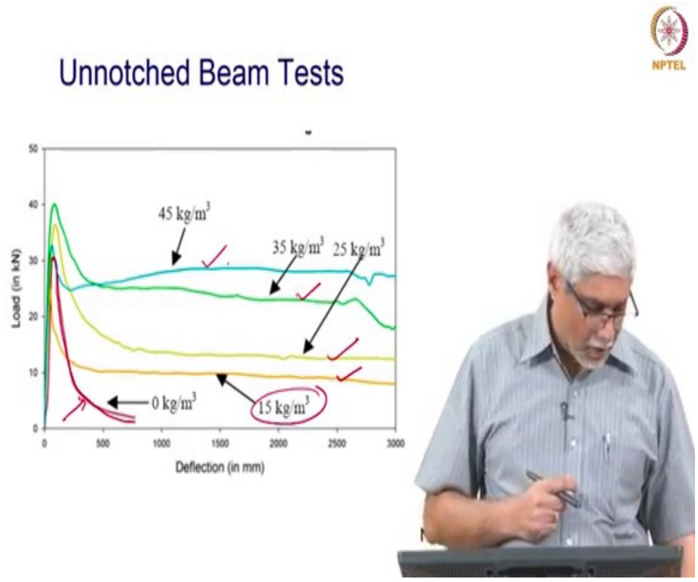

Why would we do something like that if we want to find out how the behaviour of steel fiber reinforced concrete is, In above image red line is beam without any fibers, normally in a modulus of rupture test you get sudden failure and if you control it right, you get a stable curve, you get a post peak , the same post peak now with 15 kg , 25 kg, 35 kg and 45 kg of steel fibres, so once you can do this test properly we can assess how much of fiber should we get to get a certain stress after cracking, which we can use in design of pavements and other structures.

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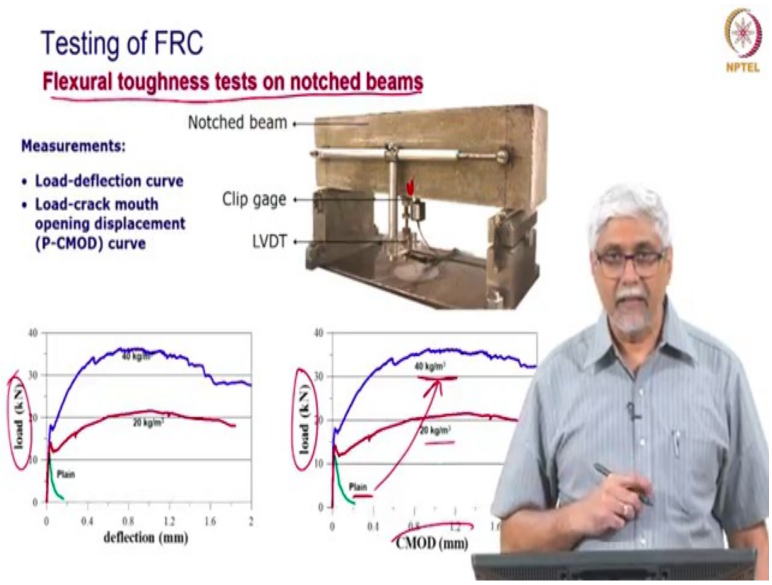

The next step is to look at notched beams where there is a notch cut in the beam and then we can put an extensometer across and we can do the measurement more easily, it is easier to get a stable test and you see some examples of load deflection or load crack opening, and again you see the influence of adding fibers, this is the plain concrete 20 kg of fibres and 40 kg of fibres and this is a way of defining the flexural toughness, so these are test also which are done in closed-loop servohydraulic testing systems.

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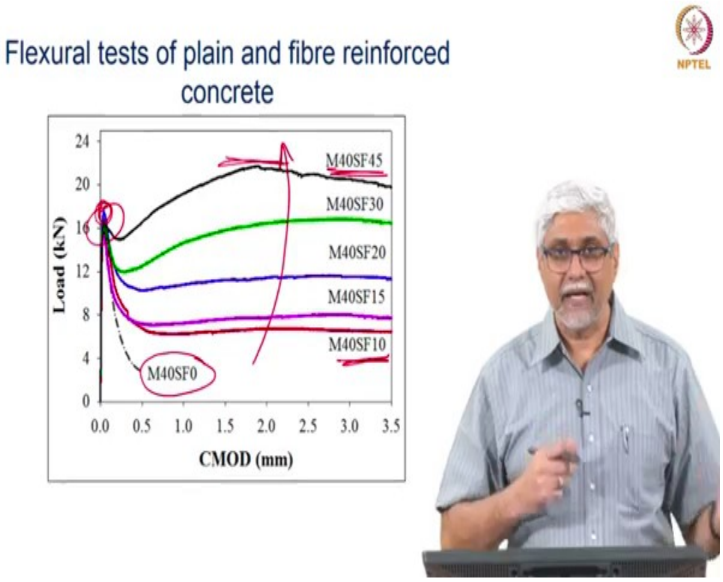

And in above image is the behaviour that you would get with a lot of test, there is an M40 concrete with no fibres, thi is from thesis of Sujata Josh, who will also be showing you some of a her test, Black line is with 10 kg and going up to 45 kg of fibres and you can see how the energy is increasing, how the load carrying capacity is increasing and you can even see that in some cases the ultimate load carrying capacity or the maximum load carrying capacity is even much higher than the crack load carrying capacity because of the fibres bridging the crack, so these are some things that you would not be able to do with load control, if you have done a load control test you will not get anything beyond the peak point, the test will finish their because the specimen will suddenly break because the machine is only trying to increase the load.

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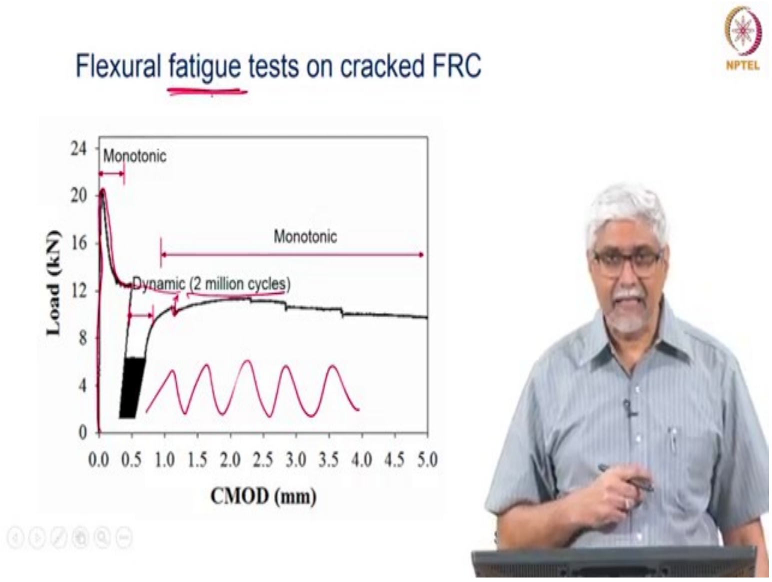

So these are test from Steffi Stephan where she is doing this notched beam test with a monotonic part, so she loads the specimen up to 0.5 mm of crack opening then she does a lot of cyclic test, so these are cyclic test to see how fatigue is behaving, then after about 2 million cycles she continues the test to see if the load carrying capacity has increased or decreased, here you see for example that there is some residual damage there , so these are test that tell us how the fatigue behaviour of the concrete would be and in this case cracked fiber reinforced concrete.

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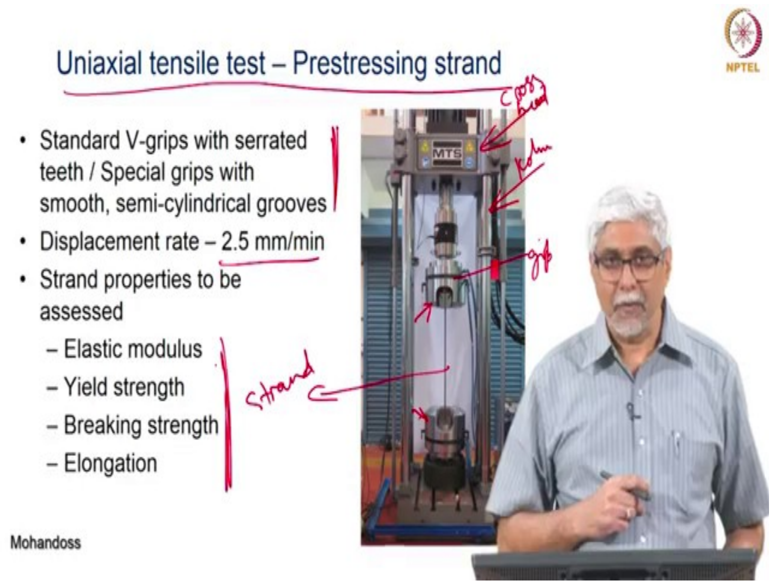

Now these are some interesting test of Prabha Mohandas who is looking at uniaxial tensile behaviour of prestressing strands, so this is the image that I showed you right in the beginning, there is the frame, these are the columns and there is the cross head , there is the column and there are the grips holding the strand, there is the strand that is being tested, which is gripped there and then we are trying to see what is the behaviour, there are the parameters and you have to gripped it properly also, so you see that you need some special grips otherwise the strands starts to slip and with this you will be able to get all this parts, all this aspects of the response which are important.

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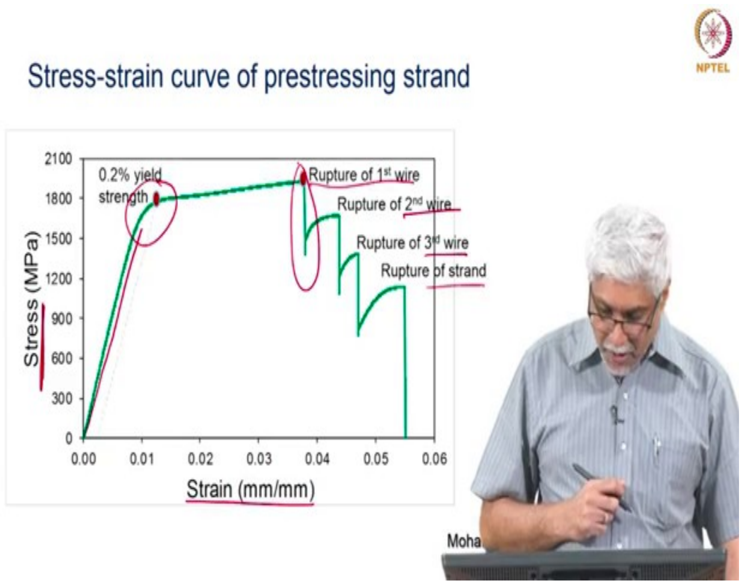

This is a typical response that you will get, this is the stress strain behaviour of the strand, you find a very nice elastic part as you would expect, that means that we are able to capture very nicely the elastic regime, then there is yield, then the load continues to increase until we have rupture of the first wire of the strand, second wire, third wire and finally the whole strand ruptures.

So this to me is a beautiful response showing, how the behaviour of the strand is as you increase the load or increase the strain and again for this we need a testing machine which can apply displacement at the same rate does not change its displacement rate or stop applying load when there is a sudden change, you see here that here wire is broken but still the machine is able to continue the test without stopping or releasing the load completely.

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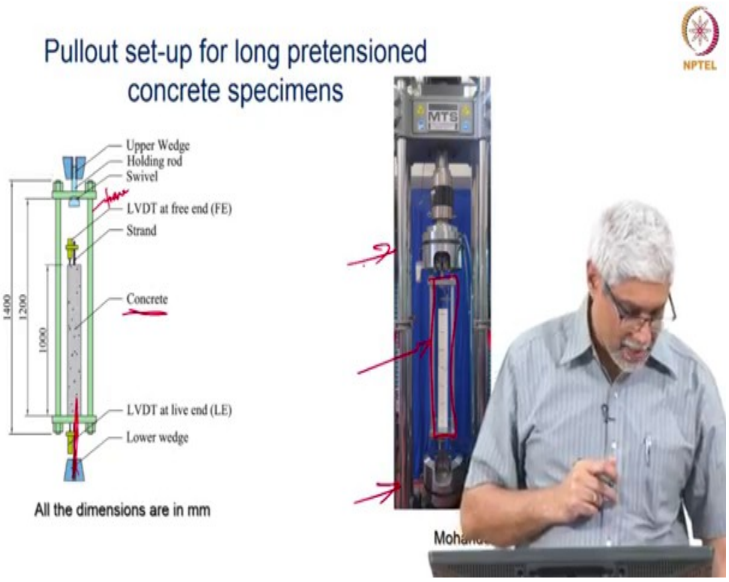

An extension of Prabhas work was to look at the pull out of prestressing strands from concrete, so this is the same machine but here instead of just a strand, now what she is doing is holding a small frame , which is attached in the testing machine and we have a block of concrete, inside this concrete there is strand, you can see the strand projecting, the strand is held at the bottom in the wedge and the frame is held at the top wedge and this whole thing is pulled such that slowly the strand is being pulled out of the concrete block .

So, the idea is to understand that behaviour and see when and how it pulls out , so this also means that we need a system that is having a large enough space that you can put this and having enough load and having a displacement stability to do this test well.

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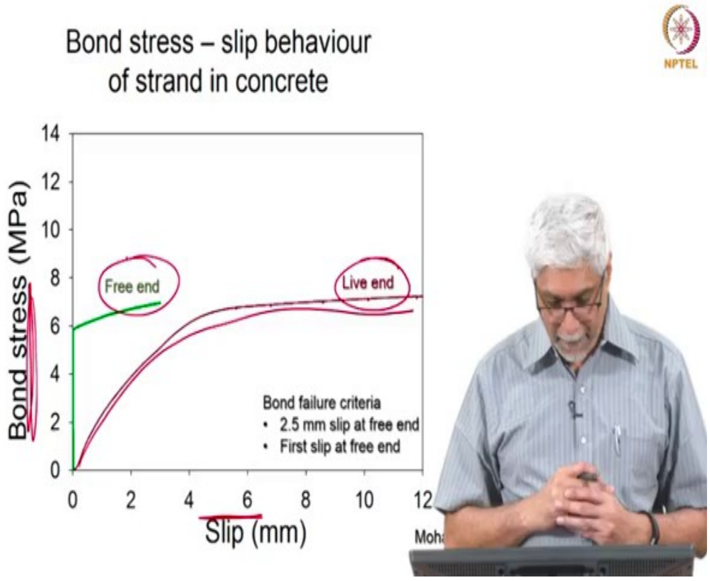

Typical response would be as shown in above image, here we are seeing the bond stress, the nominal bond stress load divided by the embedded length and the slip and here she has the relation between the stress and the slip, the live end slip, live end is what is being loaded and the free end, which is at the other end is green line type of response, so based on this she calculates parameters and there will be a video where Prabha will explain how she does this test as well.

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So, I will close with this thank you very much, have fun breaking things in closed-loop. Thank you.