Design of Masonry Structures
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Module - 05
Lecture - 39
Special Topics – Assessment of Existing Masonry Structures

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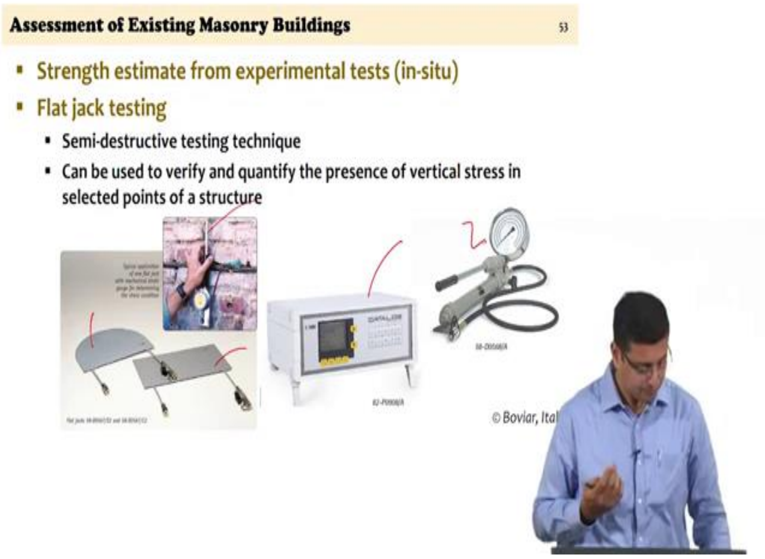

Continuing with the in-situ experiment tests, we will focus on a test called the flat jack testing today. So, the flat jack testing; there are two types of flat jack testing. You will appreciate the differences between the two types of testing depending on what you are actually looking for from the structure. The flat jack testing is classified as a semi-destructive test technique ok.

Because you can actually call it a destructive test but the level of intervention in the structure is minimal. And therefore, it can be classified as a semi-destructive test technique. What it is, primarily giving you is the level of in-situ vertical stress ok. So, what a flat jack test can actually measure is in situ compressive stress.

And this is of value because you can actually use that in situ compressive stress, which is measured from the structure and make a check against the model that you are using. See if you are getting similar in situ compressive stresses. But, a modified version of the flat jack testing actually gives you a significant advantage in being able to establish the in-situ stress-strain curve of the masonry of the composite masonry from which you can actually establish modulus of elasticity and the Poisson's ratio.

And, these are values that definitely you will use for your structural models. So, we will examine both these versions of the flat jack testing. What you see here is the instrumentation that is typically required. Our laboratory regularly does this sort of a test on existing masonry structures, but this is not a test limited to masonry structures. It is actually test testing technique that has come from geology.

This is used a lot in rock mechanics; flat jacks are used in rock mechanics. And, it can also be used in concrete structures if required. So, what you see are the flat jacks here of different shapes. You can have a semi-circular flat jack or rectangular flat jack. Now the flat jack is primarily two sheets of metal; two independent sheets of metal, which are connected to each other by welding at the edges.

So, that you create a small receptacle which can be filled with a fluid. So, what you see here attached at the ends are an inlet and outlet pipe ok. Typically oil is used, you pump oil in and then you lock the other end. So, that oil is retained you keep increasing the pressure and the flat jack will deform based on how much of oil you are actually pumping in. You need measuring devices- a simple DEMEC gauge, demountable mechanical gauge can be used.

Or you could actually have instrumentation done with linear variable differential transducers fitted on to the wall as well with LVDTs. So, the basic flat jack, the instrumentation to measure deformations and then, you can automate the whole set up with the data logger, which is constantly recording the deformations induced in the masonry.

And of course, you need a pump, you need a manual pump your operating this test at manual pressures. We do not use, we do not use motorized pumps because the level of pressures that you can generate a significantly high which can actually damage the masonry. Your intention here is not to damage the masonry and that is one of the fundamental reasons why we are calling this is a semi-destructive test.

Your intention is not to take the masonry in the wall that you are testing to failure, which is what you do in a laboratory. Here you stop probably at 50 percent or lesser of what could be the failure stress. So, you cannot go to failure, you cannot characterize till failure, but you can characterize to an extent which is sufficient for you in terms of your structural analysis ok. So, with that as the basic instrumentation, let us understand the two different types of flat jack testing called single flat jack testing and double flat jack testing. We are basically you are using one flat jack versus two flat jacks.

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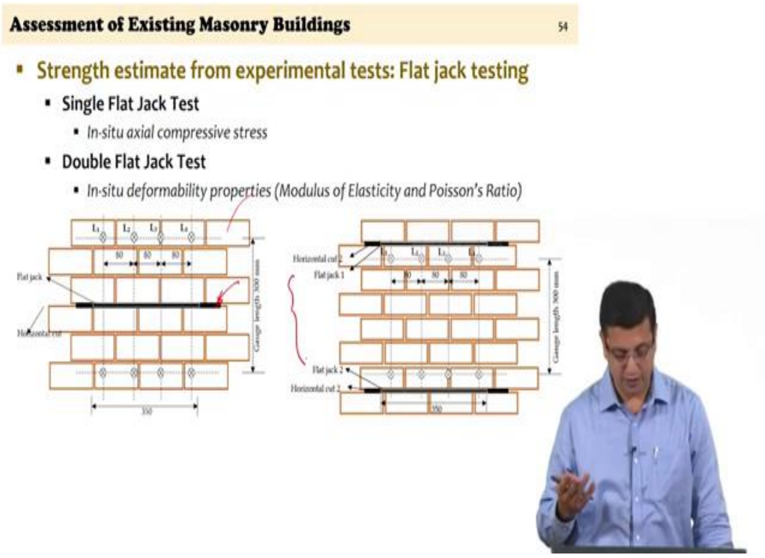

So, the single flat jack testing is meant to estimate what the in-situ axial compressive stresses. So, if I want to make an estimate of the, what is the vertical stress in a wall? Of course, vertical stress levels compressive stress levels are going to be different in different locations. So, you would make a specific choice on where you want to do this test and carry out this test.

Typically, you choose locations where compressive stress is expected to be high enough. Because when you have very low compressive stress, let us say you are testing a single storied wall or upper story of a multi storied structure in-situ compression levels will be low. The method adopted here does not work very well when the level of compression is low. So, that is something you might want to keep in mind. So, how do you go about doing this in-situ single flat jack test?

So, what you see here in the slide is the elevation of a wall. In the wall you make a slot into which the flat jack is inserted. So, you saw a flat jack is almost like a piece of paper; it is thicker than the piece of paper it is like a thin book. You are actually inserting that book into the wall. Typical dimension of a flat jack is about 25 centimeters by depth of about 15 to 20 centimeters.

So, they can actually be manufactured to sizes that you really want to work with ok. Look at the elevation of the wall, the exposed brick work is shown here. Let us say you have decided which joint to work on, it is prescribed that the flat jack be inserted in a mortar joint. You can even insert it into stone or brick unit locations; however, that would be difficult.

You would actually be damaging the masonry construction significantly to avoid that, it is prescribed that you target the mortar joint bed joint is the horizontal continuous plane available to you and insert the flat jack there. So, what is typically done is, once the location where the flat jack test is going to be conducted is identified. Before a cut is made across the line within which the flat jack is going to be inserted which is this thick black line.

Let us assume that the flat jack is not get inserted there, I established four gauge lengths- L_1, L_2, L_3 and L_4 across the length of the flat jack location. And make those initial measurements before a cut is introduced. So, L_1, L_2, L_3 and L_4 are measured and noted down that depends on the gauge length that you are working with depends on the size of the DEMEC gauges that you have or the instrumentation for an LVDT that you actually have.

So, you make the measurements L_1, L_2, L_3 and L_4 and then introduce a cut at the joint that you have selected. You make a cut, now this cut would have to ensure is large enough to hold the entire flat jack that you have made. You have actually with you; the fabricated flat jack but not too large compared to the flat jack itself.

So, the size of the cut that you make, the area of the cut that you make must be as close as possible to the flat jack itself. So, how do you make this cut? You need a rotary drill or you could use a regular drill and try to make a cut which is in the shape of the flat jack itself. So, in the previous slide you saw two shapes; one is the semicircular shape and the other one is a rectangular shape.

If I use a rotary cutter, if I use a rotary drill then I can actually get a semicircular shape as a cut. It is difficult to get a rectangular cut, in an existing wall. You can actually make it by making several punches using a drill but it is quite a messy job. A rectangular flat jack is typically used in a new construction. If you want to make a new if you want to measure something in a new construction, you can actually place the flat jack and make the construction of that joint.

However for existing buildings, the choice is typically on semi circular of flat jacks. So, the cut has to be made such that the area of the cut is not too large in comparison to the size of the flat jack; you will appreciate the reason why this is important in a moment. And then you also have to ensure that the thickness of the cut that you make is not too large in comparison to the maximum size that the flat jack itself is.

So, this flat jack is as I said thin as paper it is about 4 millimeters in thickness or 6 millimeters in thickness depending on the thickness of the two plates and the void that is there in between. So, if the flat jack is about 4 millimeters you should not make a cut which is more than about 5 to 6 millimeters. So, there is dimensional control required for the cut that is being prepared there.

Because, if you make two large a cut, the flat jack will loosely fit in the cut and then when the flat jack is inflated the contact will be lesser than the overall area of the flat jack. So, you do not want that sort of a situation, you do not want concentration of contact of the flat jack with the masonry. You want the entire area to be in contact and therefore, workmanship of the cut is an important parameter ok.

So, once the cut is made let us say the entire cut has been executed you wait typically for a few minutes. Because, now with a cut made there is going to be redistribution of loads and the stress path in the structure itself right. You have made a cut that was a resisting path now that is not carrying load anymore and there has to be redistribution occurring, there will also be deformation.

So, let us say you make a cut of 5 millimeters after a few minutes if you measure the size of the cut, it should be lesser than the 5 millimeters of the original cut, which means deformation will happen over a period of time. So, you wait for some time and then re-measure the gauge length L_1, L_2, L_3 and L_4. So, lengths L_1, L_2, L_3 and L_4 before cut length L_1, L_2, L_3 and L_4 after cut are recorded and then the flat jack is inserted.

The flat jack is inserted it is connected to the pump the oil pump the manual oil pump. And you start slowly in pressurizing the flat jack such that oil start circulating and filling up the flak jack. As you start filling the flat jack, the flat jack starts exerting pressure against the masonry. And as this pressure increases, you decide at what resolution you are going to start taking measurements.

You pressurize to a few bars and then let us say 0.25 bar and then make a measurement; make these measurements of L_1, L_2, L_3 and L_4 increased again by 0.05 make the measurements. So, what you are going to be doing is, make continuous measurements of deformation L_1, L_2, L_3 and L_4 as you keep pressurizing the flat jack.

At a certain point the flat track is now pressurizing deforming the masonry. The deformation it lost when you made the cut will be regained by the pressurizing that you are doing right. So, at some point, the pressure that the flat jack is at is adequate for the gauge lengths L_1, L_2, L_3 and L_4 to be equal to what it was before the cut. At that precise point the understanding is that the flat jack is now carrying the stress, which the masonry originally was carrying.

So, your intention is to reach that level of original deformation measured by the gauge length by the gauges L_1, L_2, L_3 and L_4 which was before the cut. And at that point the pressure corresponding to that deformation is really what the in-situ compressive stress is. However, that in-situ is compressive stress actually has to be corrected by a couple of parameters will examine that in a moment.

So, this is what an in situ axial compressive stress flat jack test would look like right. So, once you have established the pressure in the flat jack at which the deformation is same as the measurements L_1, L_2, L_3 and L_4 are same as in the original wall you stop the test. You can continue and do a double flat jack test and what this double flat jack test is really doing is giving you the possibility of measuring in-situ what is the modulus of elasticity of the masonry and the Poisson's ratio of the masonry, both parameters that you will use for your structural analysis. But how do you do that you actually use two flat jacks now not one flat jack? With one flat jack you have established what is the in situ compressive stress; with the second flat jack. The area that is between the two flat jacks, you have two flat jacks.

And, you have an area between the two flat jacks you will compress and decompress that area in increasing cycles of compressive stress you start with small compressive stress. And, then go to larger cycles compress and decompress go up to about an estimated 50 percent of the compressive strength of the material. As I said you do not want to make the masonry fail in this test, it is an in-situ test; it is not advisable that the wall that you are working on. You take it to failure as you are standing there and testing.

So, you take it to about 50 percent of the peak strength that you think the masonry should have in this particular case. And then go through loading and unloading cycles and you arrive at the stress strain curve from this from this from this double flat jack test. From the stress strain curve if you have instrumentation along the vertical axis, you will be able to arrive at the modulus of elasticity with instrumentation in the lateral direction.

If you have LVDTs in the lateral direction lateral bulging can also be measured and you can get an estimate of the Poisson's ratio. So, in-situ deformability characteristics you require a double flat jack test single flat jack test is particularly for the axial compressive stress.

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So, there are a couple of standards well established standards for how single and double flat jack tests can be estimated; can be conducted. One of them is the RILEM standards we were talking about RILEM in the previous lecture. It is a network of European laboratories and a number of test techniques are formalized through RILEM.

And the second standard is the standard from the united states- the ASTM standards that you can refer to the numbers are reported here. So, what you see here is a historical masonry structure in brickwork and lime mortar in which a double flat jack test is being carried out. And you can actually see how the gauges the pumps are connected to the wall.

And you can actually see four vertical gauges, LVDTs which are measuring the vertical deformation. And you can see one horizontal which is actually measuring the lateral deformations in the masonry. So, I have axial deformations, I have lateral deformations I can estimate both modulus of elasticity and the Poisson’s ratio in-situ. So, this is how the test is executed it is cumbersome.

And as you can see plaster is removed, the brickwork is exposed and then you conduct this test. So, a single test may take a few hours four to 5 hours to actually execute. But, can give you valuable in-situ information because the sample now is an undisturbed sample. The state of stress in it is actually not disturbed.

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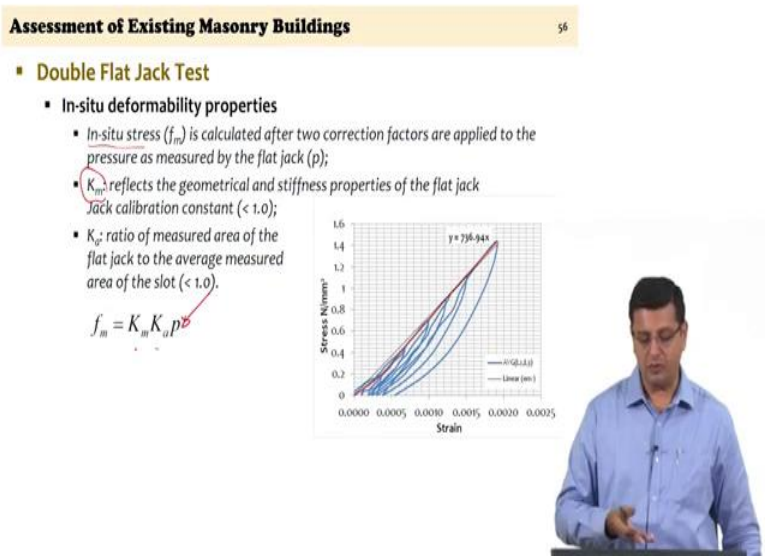

So, how do you arrive at what the stress levels are? So, you need as I said earlier, couple of correction factors, these correction factors come from two physical quantities that you really cannot physical parameters that you cannot overcome beyond a certain point. So, what you actually do is, take the pressure that the hand pump is actually giving you at a certain point in time in making measurements.

And use that to calculate what the in-situ compressive stress is, by multiplying it with to correction factors, the first correction factor. So, that is what the stress strain curve would look like as I said the blue line shows you the stress strain curve, but these are actually compressions and decompression.

So, loading and unloading, loading and unloading. And each cycle we are taking the masonry to a higher and higher level of compression that is why these loops are increasing in size. And, as you see we are still in the linear elastic range we do not go beyond the linear elastic range. Because we do not want in situ damage due to this test. And so from this test from the backbone curve it is possible to arrive at the modulus of elasticity and use that in your calculations.

If you have two or more locations you can actually take an average of these values and you have valuable information coming from the structure itself. So, the correction factors the first correction factor is a stiffness correction factor. It basically reflects the geometrical and stiffness properties of the flat jack material. So, the flat jack as I said is two metal plates which are welded to each other.

And therefore, as you pump oil and this starts expanding, it depends on the stiffness of the metal before it starts deforming. So, if you have a very stiff metal plate with which the flat jack is made, the stiffness of the plate will contribute to the in situ stress level ok. If the plate is highly deformable, of very low stiffness, then it will not contribute significantly to the in-situ stress level.

But, if the plate is really strong and stiff and strong, then it will take additional pressure for the plate to deform before the masonry comes into contact and the actual in-situ pressure level is measured. So, this is called the jack calibration constant. This jack calibration constant is typically provided to you by the manufacturer of the flat jack by doing a standard test and estimating what should be this correction factor.

So, typically a correction factor which is less than 1 is arrived that and you multiply that with the in-situ stress level p. So, it is a flat jack pressure let us say the flat jack pressure is p; you multiplied the K_m factor to this and it will reduce the in situ pressure; we actual estimate of the in situ stress f_m. The second parameter and that is the reason why I said it is important that the areas of the flat jack and the area of the cut are as close to each other as possible.

Because, if you make a large cut and then insert a small flat jack. The actual redistribution area of load is much larger and that is going to be carried by a flat jack which is significantly smaller which could mean concentration of stresses. You do not want that sort of a situation and therefore, there is a cap on this ratio between area of the flat jack to area of the cut itself.

And typically we target about 80, 85 percent as the size of the flat jack area of the flat jack to the area of the cut itself, but this also must be measured. So, the K_a factor is nothing but area of the flat jack divided by area of the cut; again less than 1 and try to keep this value at about 80 percent or higher. And then you are in situ stress level at each point that you take the measurement is nothing but the in situ flat jack pressure p multiplied by these two factors.

So, you know that fm will therefore, always be less than p; but that is that is how it is because these two factors actually contribute to. The higher stress than actually there is in the wall itself because of the stiffness of the plate and the differences in the areas. So, this is how you actually carry out the double flat jack test in the single flat jack test.

And, as you see you have very valuable information, which you can use in your structural modeling. In fact, the in-situ stress level can be used for your checks, even your hand calculation in terms of what the axial compressive stress level should be can be compared to values coming out of the flat jack test. And the double flat jack test values can directly be used in terms of modulus of elasticity and Poisson’s ratio in your structural modeling calculations ok.

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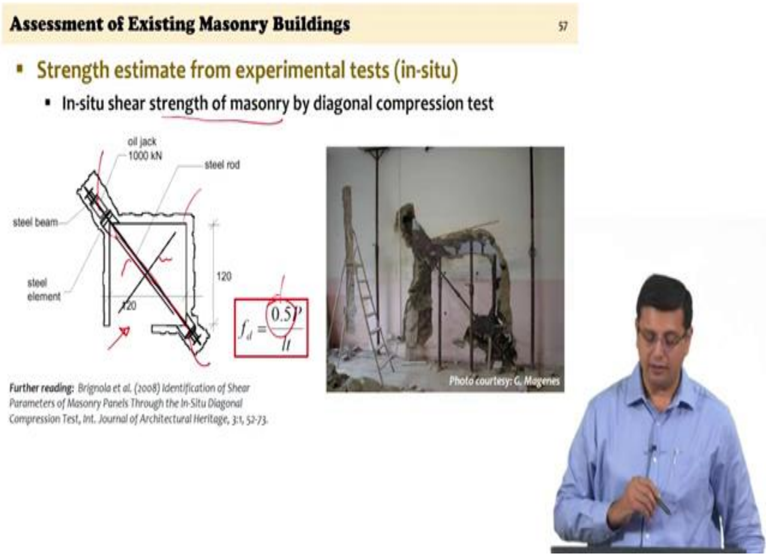

Continuing with in-situ tests, this first test is actually looking at compression behavior right. We looked at wallettes, we looked at cores which are looking at compression behavior. We looked at the flat jack tests which is again looking at a compression behavior right and deformability under compression.

But you know that when you are looking at earthquake assessment, shear strength becomes important. Now, you can establish the shear strength knowing the compressive strength; because typically compressive strength and shear strength are correlated ok. However, remember that any of these correlations are empirical and which would mean given the variability of masonry these empirical coefficients can also be different.

So, in the worst case you can arrive at the shear strength, knowing the compressive strength by correlation. However, there are also some where you want to be rigorous, you can actually conduct some in-situ tests. And arrive at what the shear strength of the masonry is which is again very valuable as far as your seismic assessment is concerned.

So, couple of in-situ tests the first one is to estimate the shear strength of masonry by the diagonal compression test. We have looked at the diagonal compression test and an ASTM standard that actually regulates the diagonal compression test. You can arrive at the tensile strength of masonry; because failure is by diagonal tension mechanism principle tension mechanism.

Similar tests can be done in-situ, it requires a lot of gymnastics in the site. But, it is something that is feasible. And, particularly when you are working on existing buildings seismic assessment of such buildings, where you have sacrificial walls; where walls are actually going to be toned down because of alterations being made or because of heavy damage.

So, building is going to be pulled down then that presents you a wonderful opportunity to actually execute such a test; because it gives very valuable in situ information of shear strength of masonry. So, this test requires that if you remember the laboratory tests required a wallette of size 1.2 meters x 1.5 meters ok. Now when you are doing this test at the site it again requires that you have 1.2 meter x 1.2 meter wall panel on which you are working.

Now let us imagine that there is a load bearing wall on which you are allowed to do this sort of a test. It means that you should be able to isolate this wall panel, but not completely right. So, what you see here is, almost four fifths of the panel has actually been isolated, what you see here is a gap in the wall that irregular area around the wall panel of 1.2 x 1.2 meters is a gap that is running all around.

Because you actually need to introduce diagonal compression to introduce diagonal compression you need the loading frame. So, you need a cut sufficient enough to be able to insert the jack and the bolting mechanism. So, what you see here is the jack that is introduced at this end the reaction frame here and bolting. So, you have the steel rods running on two sides of the wall, which is then tightened.

And then the jack can actually introduce the necessary diagonal compression. And then you make measurements along two diagonals that being one diagonal and that is the other diagonal. Of course, there is going to be a certain difference between such a test and the laboratory test because of this area which is still in contact with the wall. Because, if you isolate the whole thing; it is as good as taking it out taking it to a laboratory and testing it.

So, this is as in-situ as you can actually get as far as this test is concerned but mind you, we are getting the shear strength of masonry by this test. You can actually see a picture here where the cut is made you can see how large the cut actually is. And, then the jack is introduced and you can conduct this test on the wall; there are some interesting.

There are some interesting research work that is available which you can use to understand are there any other variations to this test that is possible and what are the basic recommendations in terms of conducting this test itself? You do not have a standard to conduct this test, it feeds into the ASTM standard, which is the standard required for testing diagonal compression the testing masonry wallets in diagonal compression itself.

And as we had seen earlier, the failure load is then used to estimate the shear strength of masonry. And if you remember this 0.5 is really coming from an understanding of at what levels of stress is the diagonal tension. The principal tension failure expected to occur and comes from some non-linear finite element studies as well.

Because it is not it is not the entire area of cross section of this diagonal but something lesser. So, Plt/2 is what you would actually used to estimate the shear strength of masonry here. And, as I said there is some interesting studies that you can actually look into if you are further interested; I have reported the reference here. So, that is for the test on masonry shear strength: but if you want to actually get the joint shear strength right.

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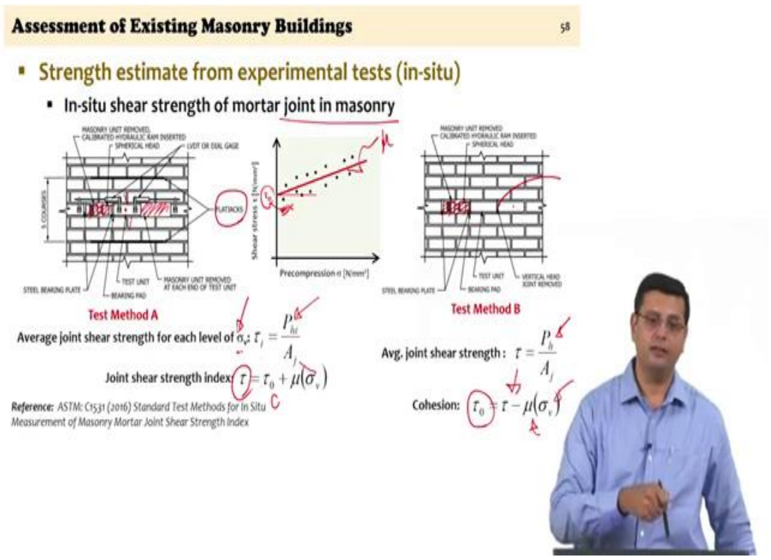

We talked about the difference between the masonry shear strength versus the shear strength of a mortar joint in masonry. Even that is a test that can actually be executed. In-situ it is less scarier than the previous test in terms of its requirements. But, you have standard test method here; I am referring to ASTM 1531. ASTM 1531 actually gives you the possibility of conducting this test in three different ways.

I am discussing a couple of them here test method A requires that in a wall in which you want to actually establish what the joint shear strength is, you have to make two cuts; this is the jack what you see at the centre is the jack. But on either sides of the jack on the two sides of where the jack is the jack is actually fixed on to a central brick unit.

Where the red dot is one brick unit that brick unit is retained. The two brick units on either sides on the left and the right of the central brick unit are removed ok. You physically remove the two brick units by cutting along all the sides. And, then on one side the jack is introduced and the other side is left vacant right. So, this is a gap this also was a gap.

But that is where the jack is introduced; because that is the jack that is going to provide the shear force required for the two joints upper and lower bed joints of the brick in the middle right. So, test method A the important difference of test method A are these two flat jacks right. If you remember the lecture on joint shear strength, there is a sensitivity to the level of pre compression.

So, test method A requires that, you introduce flat jacks at the top and bottom of the test location and control how much of in-situ compressive stresses being applied. You cut an isolate put flat jacks there and measure exactly how much of pressure you want to introduce in the masonry. So, that an estimate of the in situ compressive stress is known to you as you do the test for the shear stress.

So, once the flat jacks have been pressurized, you know what the in-situ axial stress is that you are maintaining in the masonry panel. Then conduct the shear test the brick fails. There are two surfaces upper surface and lower surface together which is the shear area, you would be able to estimate the shear stress corresponding to a certain level of axial compressive stress.

So, here for each level of vertical compression, you will establish, what is the average joint shear strength which is the pressure at failure P_{hi}. That is the horizontal pressure at failure I referring to the level of pre compression that you have established using the flat jacks divided by A_j. A_j is nothing but the sum of the areas of the top and the bottom of the brick which are the two bed joints which are subjecting to shear.

Once you do that, you keep doing it for several levels of pre compression. And you remember this picture, where for different levels of pre compression you have different levels of failure stress. All those black dots are what you will get once you have all those black dots. Then the intersection of the best fit line this red line being the best fit line intersection of the best fit line will give you tau naught.

This τ_0 is the cohesion that we have talked of earlier. In format where you have the shear strength is $c+\mu\sigma_v$. So, the joint shear strength with this technique from the graph that has all the points different levels of σ_v you will be able to establish what τ_0 is, which is nothing but the intersection with the vertical axis.

And then the slope of the best fit line is going to give you μ. Slope of this best fit line is going to give you mu. So, you have μ you have τ_0, you know the level of pre compression at each level. And therefore, you will know the joint shear strength from such a test. If this test cannot be implemented with the presence of flat jacks, the problem is you do not know what is the in-situ compression level, that is the problem.

So, method B actually allows you to do this test, but without the flat jacks. So, in this case you are actually removing a masonry unit in this slot, you are creating a cut here. So, that head joint is removed and you do not remove the unit next to it, you do not necessarily need to remove the unit next to it if you want you could remove it.

But even if you remove the head joint that is sufficient and then only the jack is the horizontal jack is operated, when the joint fails you will see movement. And here the problem as I said is you do not know what is the vertical compressive stress level. So, in this technique the average joint shear is calculated as the failure load P_h now there is no index 'i' because it is at one level of pre compression, divided by A_j that remains unchanged but you get only one value. And then you will actually have to assume the value of mu you do not know the value of μ. You will also have to make an estimate of what σ_v is and then get an estimate of τ_0 as τ which will establish from here; minus assumed value of μ into estimated value of σ_v.

So, the two test methods are useful test methods to give you joint shear strength. And they operate in different ways with or without the knowledge of the with or without the knowledge of the in situ vertical stress. So, where you have the possibility, these are tests, are minimum tests that can be conducted. In situ to make your assessment quantitative assessment robust with values coming directly from the field sigma v is determined.

So, in this test you saw the flat jack test that we are looked at earlier; you will actually be able to measure what is the pressure in the flat jack. So, you determine how much pressure you want in the flat jack and that determines how much that masonry panel is subjected to in terms of pre-compression. So, you would want to choose 5 or 10 different levels of pre compression.

And change the amount of pressure you put the flat jacks into and change the pressure in the and therefore, change the pressure in the masonry. So, you have a measure of the in-situ stress and use that value keep it at that value and then conduct the.

Student: Pre-compression.

It is pre-compression, it is like the point is if you look at one world in a structure, it has one at is given point it has one value of pre-compression. But, you know that the shear strength joints shear strength varies with the pre-compression. You want to establish that relationship to establish that relationship but not in the laboratory in the site, you need to be able to regulate the vertical pre compression level. And this is a method which allows you to be able to use flat jack plus the lateral jack together to establish that.

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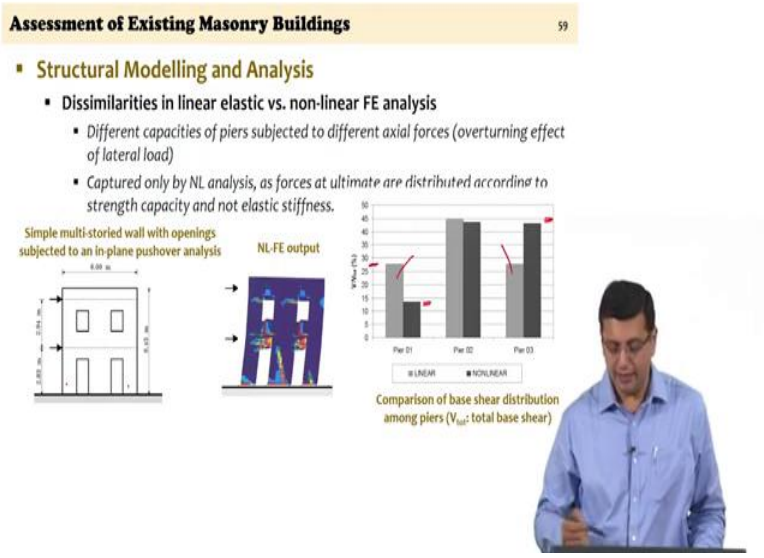

Having spoken of in the last few slides, from the last lecture on estimating residual strings and I think that is one of the fundamental things that you need to be aware of as far as structural assessment or seismic assessment is concerned. The second important thing that I want to focus on is the possibilities and the requirements of structural modeling and analysis right.

So, you do you are working on existing buildings. And, you are working on existing masonry buildings which I hope you will agree with me. Now, have a structural behavior which is different from moment resisting frames right. So, most modeling software are designed are configured keeping in mind moment resisting frames. If you look at your standard structural software like: STAAD or SAP or any other ETABS and so on.

Most of them have actually been conferred configured keeping in mind structural behavior of a moment resisting frame. Or shear walls, reinforced concrete shear walls or reinforced shear walls. Masonry structures have a different lateral load resisting mechanism as we have been seeing during the course of this course, during the lectures of this course.

So, when it comes to structural modeling and analysis there are certain things that we need to keep in mind. And also examine what possibilities we have. So, I am going to spend some time looking at these aspects. So firstly, should be we doing linear elastic analysis is it to do linear elastic analysis. As far as masonry is concerned or should be actually we doing non-linear finite element analysis for example, right.

The fundamental question is linear elastic analysis when you are doing seismic analysis ok. That's the fundamental question. And, you know that code will actually allow you to do linear elastic analysis. The code is ok, seismic code is actually allowing you to do linear elastic analysis. You can do an equivalent static analysis, you can do linear dynamic analysis, you could do a response spectrum analysis these are all permitted by the code.

Now the question I am examining here is it to do linear elastic analysis as far as masonry constructions are concerned ok. What dissimilarities should you be aware of when looking at seismic analysis for masonry constructions? If you compare them to non-linear finite element analysis, let us look at a simple example that is a masonry wall. You could look at a full structure but we are interested in looking at a wall here; it is multi storey, it is two storied and it has openings.

So, we are looking at a perforated shear wall two storied which is subjected to its own self weight and lateral forces ok. So, we are looking at a wall which is subjected to increasing lateral forces under its own gravity force. So, pushover analysis to be specific. You have seen in the examples that we were looking at when examining system level design of masonry constructions; we looked at how when you are looking at seismic analysis, the lateral forces create overturning moments because of which different piers here you have three piers and outer pier and inner piers two outer piers and one central pier. Because of the lateral force and the overturning movements in the the three piers the axial load levels are going to be different in the three piers they are not going to be the same; they are not going to be the same.

So, the piers actually because of different levels of axial force, you have an axial force coming from gravity over and above. That you have an axial force, which could be compression or tension coming from the lateral force the earthquake force. Now, because of that the pre compression level in the masonry pier is different at each location, which means the capacity is going to be different and is going to depend on whether or not the overturning effect is accounted for ok.

Now if you were to do linear elastic analysis, this aspect is not accounted for because the same pier at different levels of pre-compression can fail at different levels of shear force. So, this is something which needs to be accounted for which a non-linear analysis program, Non-linear analysis method will actually be able to account for which is this pier here.

And this pier here will not fail at the same values of lateral force that difference can be captured only if you use a non-linear approach to estimate the response of the wall to lateral forces. Now so, what your question is why would these forces be different the question is why would these forces?

Student: Similar specification of the pier.

Yes, see the geometry is exactly the same the material is exactly the same. But the axial load the axial load, which is due to the overturning effect for coming from the lateral force is going to a situation where the left pier maybe in tension, the right pier may be in compression. Now, because of the changed pre-compression levels the force at which it fails will be different.

So, if you were to go with a linear elastic analysis, the linear elastic analysis is going to tell you that two piers pier one and pier three will fail at the same level of lateral force. However, the non-linear analysis will tell you that pier one is actually going to fail at a significantly lower level of lateral force; because it is decompressed that can be captured only with a non-linear analysis.

And, the problem is not so much in terms of the distribution of forces initially based on the elastic stiffness. But, what happens at ultimate and what happens at ultimate determines the failure and that cannot be captured in an elastic linear elastic analysis. So, this particular the distribution of forces at ultimate depending on the level of: so the strength capacity being determined by this unequal distribution coming from the effect of the axial force coming from the overturning effect cannot be captured by the linear elastic analysis. Linear elastic analysis we will just use the linear elastic stiffnesses and tell us that the level at which the two piers are expected to fail is the same, but it will not be the same. So, fundamental issue that you will have to confront is is it to use linear elastic analysis approaches modeling and analysis approaches for doing seismic assessment of masonry constructions?

And, it is best if you take an approach which accounts for the non-linearity in the construction. And, this is something which is which is important for you to understand. You can go completely wrong in terms of loads at which these individual elements can fail ok.

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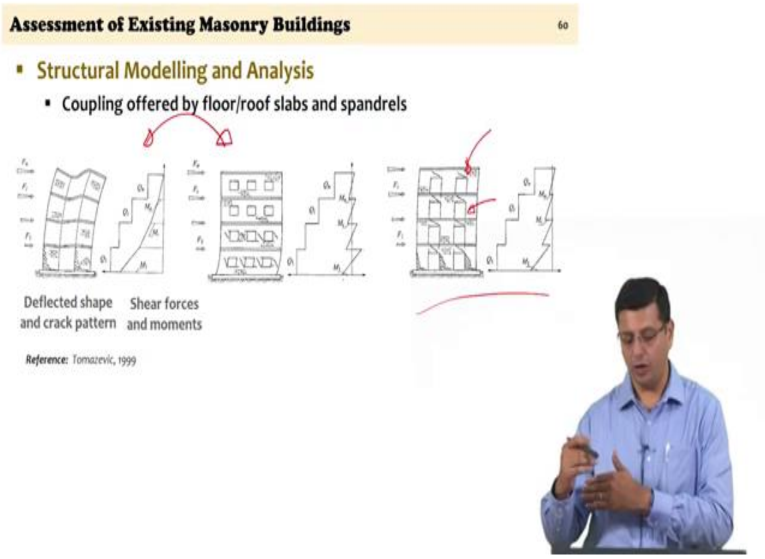

So, therefore, what options do you have? And this is something that gives you the basis to choose a certain modeling and analysis approach versus another. So, we have seen that the role played by a rigid diaphragm and the role played by a spandrel is critical in terms of how the pier behaves in terms of its boundary conditions right.

We looked at how a perforated wall has fixed boundary condition versus a cantilever. Boundary conditions when these openings are not present. Plus, it is also important to have rigid diaphragm action. And, if it is a structure which has a flexible diaphragm then we have seen how this critical difference changes the way the forces are distributed to the walls; the lateral force is distributed to the walls.

So, it is important to understand that depending on the structural configurations you can have differences. So, if you were to look at case where you have no openings for example, and just a shear wall which is multistoried shear wall in the masonry construction. You could have a deflected shape due to the lateral forces which is closer to a cantilever deflected shape right.

So, you have the maximum overturning movement, maximum base shear at the bottom and reducing all the way to the top of the structure. So, it is possible to idealize in this particular sort of a scenario it is possible to idealize the masonry structure as a cantilever beam; if you were to adopt the sort of a frame modeling approach. However, if you have openings if you have openings then the possibility is that it would not behave like a cantilever.

It will start behaving closer to a shear deformation profile and the piers will now start undergoing double curvature ok. So, how do you tackle this? This is an important understanding of how the structure will behave. And the modeling option should be able to capture the possible double curvature that is expected in the in the piers themselves.

And, you could have a situation which is actually in between the two. The second one that you looked at is again an extreme where the spandrels are really strong and acting as rigid couplers between the piers. And so, you have a uniform double curvature between, I mean in each pier along the height.

In reality the spandrel also will deform it is not a rigid element and that can actually, bring us to a situation which is actually in between these two. It can it is somewhere between a cantilever profile and a shear deformation profile, which means you must have apart from the piers some way of handling, how much the spandrel is deforming and how much coupling is happening between the piers.

So, this is the realistic, the third case is really what is closer to reality where you do have boundary effects, because of the stiffness and strength of the spandrel. And, you must have a model that can actually account for both the strength of the pier stiffness of the pier; strength of the pier spandrels and the stiffness of the spandrel.

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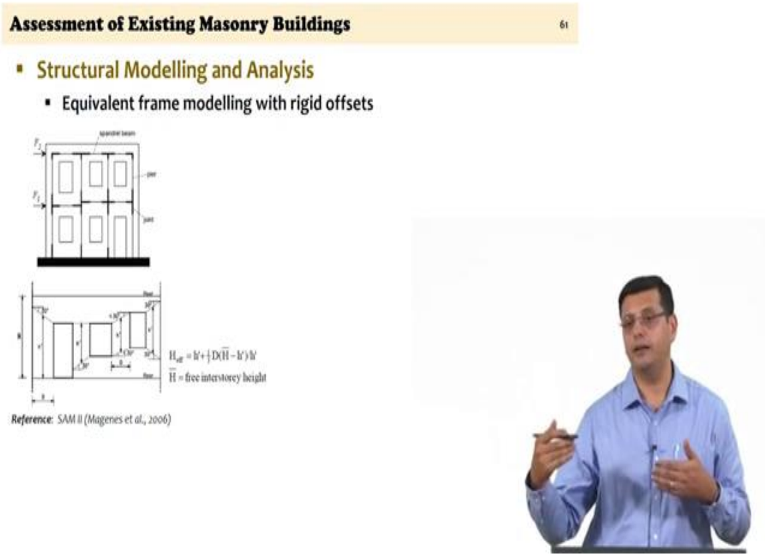

And therefore, what we will examine from the next lecture is how you could actually model a masonry structure using an equivalent frame approach. That is, you make a frame model, but based on the understanding of how these horizontally aligned spandrels and vertically aligned piers can actually be modeled. So, we look at that in the last lecture on how you could do an equivalent frame modeling with non-linear parameters for the masonry itself.

Thank you.