Design of Masonry Structures
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Module - 02
Masonry Materials and Properties Part - VI
Lecture – 10

Good morning; we will conclude the part on the Masonry Materials and Properties examining the different strengths of the constituents and the assemblies by looking at masonry in shear. So, that is the part that we were examining at the end of our last lecture.

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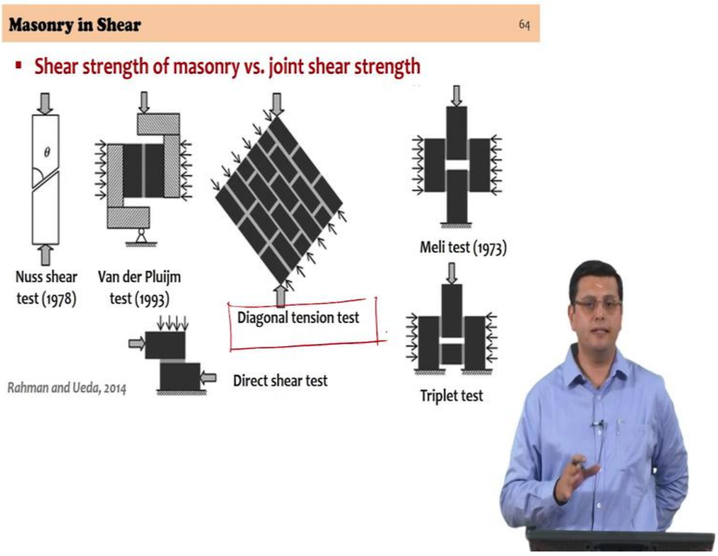

Fundamental aspect that you need to keep in mind is when you are examining the shear strength of masonry you will have to distinguish it from the joint shear strength. The joint shear strength is dealing with the bond between the units and the mortar. So, the joint shear strength establishes the strength present in shear between the unit and the mortar. The shear strength of masonry is affected by the joint shear strength but is not the joint shear strength, ok.

So, the shear strength of masonry is a mechanical parameter that is not straightforward to establish. It is fundamentally difficult to create conditions of pure shear in the first place-experimentally challenging, but is affected by other factors as well which the joint shear strength does not account for. So, it is important to understand that we are dealing with two different phenomena in this context.

So, I gave you an overview of the different tests that are conducted to characterize shear strength of masonry and shear strength of the joints. You will appreciate the fact given these differences that exist between the different test methods that really there is no consensus in the scientific community on one single test that characterizes the either the joint shear strength or the shear strength of masonry.

So, I had concluded my previous lecture presenting the different types of tests that are available in some codes and in the literature that examines shear strength of masonry and joint shear strength. Of these ,except for the diagonal tension test, the one that you see in the center here, the diagonal tension test, all the others are actually examining the joint shear strength.

The first test that you see there the nuss shear test is like actually examining over one single joint the load at failure in shear. All the others are examining one or two brick unit mortar joints under the action of shear. It is the diagonal tension test, the one in the center, we will examine in a moment which characterizes the shear strength of masonry ok. Of course, this is also not a test that is free from certain assumptions and difficulties in executing as well.

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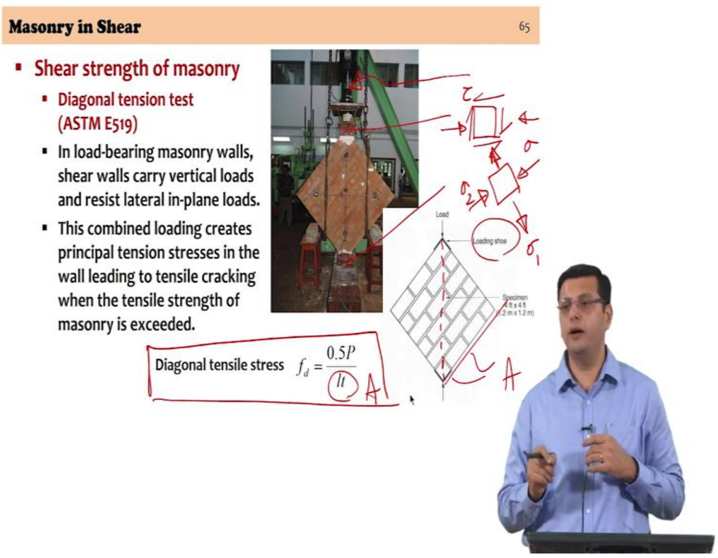

So, let us first examine the diagonal tension test and we are actually characterizing the shear strength of masonry with the diagonal tension test. There is an ASTM standard, we do not have an Indian standard that regulates the testing under the diagonal tension condition, diagonal tension test condition. The ASTM standard E519 gives the protocol for testing. It is also referred in the literature as a diagonal compression test and in a moment you will agree with me why the nomenclature.

Now you know that in masonry walls; in load-bearing masonry walls, if it is a situation where you have both gravity loads and lateral loads, the load bearing walls are simultaneously resisting the gravity forces and the lateral forces. So, if you look at masonry wall, it is really in a state of biaxial stresses. You have stresses due to gravity and you have stress is due to lateral forces acting on it. So, these it is this condition that actually brings us to the basis of a test such as the diagonal tension test.

So, when you have two different actions it is important to examine the principal stresses because you have a combination of stresses now and the principal stresses examined under the action of shear stresses in the wall, and normal stresses due to gravity become important as far as the failure criterion is concerned.

So, when the, considering that we are looking at a material which is weak in tension, strong in compression, when the principal tension approaches the tensile strength of masonry, you get failure in the masonry panel, right. So, in this it is important to examine the principal stresses and we are concerned more about the principal tension. Failure occurs under a combination of the lateral force and the gravity force when principal tension approaches the tensile strength of masonry, right. So, in a way this test is actually characterizing the tensile strength of the masonry for you. So, the literature also refers to this test, in some parts of the literature, as conventional tensile strength test of masonry, right.

So, the standard that we are talking about ASTM E519 experimental methods so, we are actually looking at a wallet and the wallet is of a size 1.2 meters by 1.2 meters. So, it is a significantly large test specimen; you have to have at least three of such specimens. The masonry wall is constructed with a single stack of bricks, right. Now, of course, you will have this point in mind that the shear strength is going to be affected by the bond; of course, it will be affected by the bond but the test protocol gives you the possibility of working with a single unit construction.

So, you have a stretcher bond and that is the thickness of the wall. So, if it is 100 mm wall; 100 mm unit then it is 100 mm wall that you are constructing in this manner. Of course, you construct it keeping it flat and then it is transported and put into the loading setup. You can see a loading shoe, a metallic loading shoe at the top and at the bottom; prescribed metallic loading shoe is what is used for uniform transfer of the compression that is applied onto this system. Under the action of compression, it develops tension; it is unconfined on the sides it develops tension along the other diagonal and you will have failure in the masonry. So, we will examine the setup and then discuss about the rationale behind this sort of a test.

So, as you see in the photograph here, you can see that axial compression is being applied using the actuator at the top. You have the actuator there and then the loading shoes are seen at the top and the bottom and these subject the masonry panel along the diagonal into compression, and failure is going to be due to the tension across the diagonal itself.

So, if you are basically considering a combination of gravity forces and lateral forces; the state of stress is actually going to be that of shear stresses and compression right. So, under this sort of a situation where you have normal stresses acting on the material and shear stresses acting on the material you are interested in examining the principal stresses. So, if you consider a state of pure shear stress, then your principal stresses can be considered on a 45 degree rotated plane, but depending on the magnitude of the normal stresses you know that the principal stress direction would change.

So, basically you would have a situation of principal stresses acting with tension and compression, and failure is expected to occur perpendicular to the direction of principal tension. So, the test setup tries to replicate this sort of a situation and hence diagonal compression is being applied, you expect failure to occur perpendicular to the direction of diagonal compression.

So, if you actually examine the test setup the compression load is actually acting along this line and if you take the area of cross section; if you take that area of cross section with respect to the area of cross section of the wall itself A, then the diagonal is basically a much longer area of cross section right.

However, it is seen that if you were to take the total load and divide it by the area of cross section given by the vertical dotted line that I have shown here; you do not get the right estimate of the failure load or the stress at which the failure is occurring. And hence a correction factor has been introduced to account for the right value at which failure occurs and the diagonal tensile stress at which you get failure is about 0.5 times the load at failure P divided by l into t.

$$\text{Diagonal tensile stress, } f_d = \frac{0.5P}{lt}$$

So, this l into t is the area, if you were actually going to be considering the area of cross section along the dotted line that should actually be 0.707 divided by A; however, if you take that value you are going to be overestimating the stress at failure instead. After a differences between few codes, we adopt this value of 0.5 divided by A as the 0.5 P divided by A; A being the area of cross section length of the specimen into the thickness of the specimen as the diagonal tensile stress at failure.

So, this provides an estimate of the shear strength of masonry; the referential or the conventional tensile strength of masonry because the failure is clearly due to the principal tension approaching the tensile strength of masonry, right. However, the other aspect that you need to keep in mind is here depending on how strong the joint shear strength is, the bond between the mortar and the unit, the failure can occur either along the interface in the form of a stepped crack or fail by splitting the unit is themselves.

So, you can have what is called a line crack splitting the unit or you can have a stepped crack that actually follows the pattern of the courses the joints and that is typically when the joint shear strength is far lower in comparison to the tensile strength offered by the unit itself.

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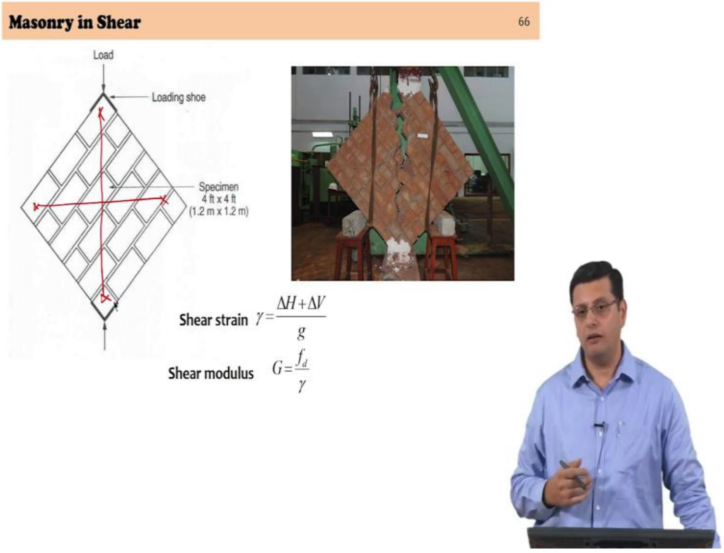

So, if you were to examine the failure pattern you can see the line of tensile cracking parallel to the line of application of the compression and as you can see in this particular figure in this particular picture, you have a combination of line and unit failure. So, the bed joints typically are stronger than the head joints. Yes, the bed joint is the horizontal joint, the head joint is the perpend or the vertical joint between the brick units.

The strength of the head joint and the bed joint is typically different. Could you think of a reason why? It is the same material, it is the same interface only the position only the direction of the of this the orientation of the joint changes, and why should one expect a difference between the head joint and the bed joint? For unit area of the head joint versus unit area of the bed joint, the head joint is weaker and that is the right answer; is that the bed joint is consolidated by the weight of the construction itself. The head joint has no way of getting consolidated under precompression.

So, the head joint is typically a weaker joint and more variable a joint than the head joint. So, in this particular case we can see that the head joints have actually given way, but the bed joints are strong enough and tend to end up breaking the bricks as the line crack is propagating. So, you should be able to examine the failure mechanisms in such context both from the perspective of bed joint to head joint strengths versus unit tensile strength versus the joint shear strength itself. However, this test here is actually giving us the shear strength of the masonry itself.

Of course, by instrumenting this, you can capture deformations. So, you can estimate the shear strain because you are estimating the shear stress at failure; you can also estimate the shear strain and look at the stress strain in shear behavior of the masonry itself. So, you can estimate the shear strain by having measuring devices typically an LVDT linear variable differential transducer that is placed across the unit, across the wallet you measure the deformation in the horizontal direction deformation, in the vertical direction and with the fixed gauge lengths that you are looking at the shear strain can be estimated as the difference in the horizontal the length in the horizontal direction. The length in the vertical direction divided by the gauge length from which with the estimate of the shear stress and the estimate of the shear strain, you can get an estimate of the shear modulus from the different stages of the testing itself ok.

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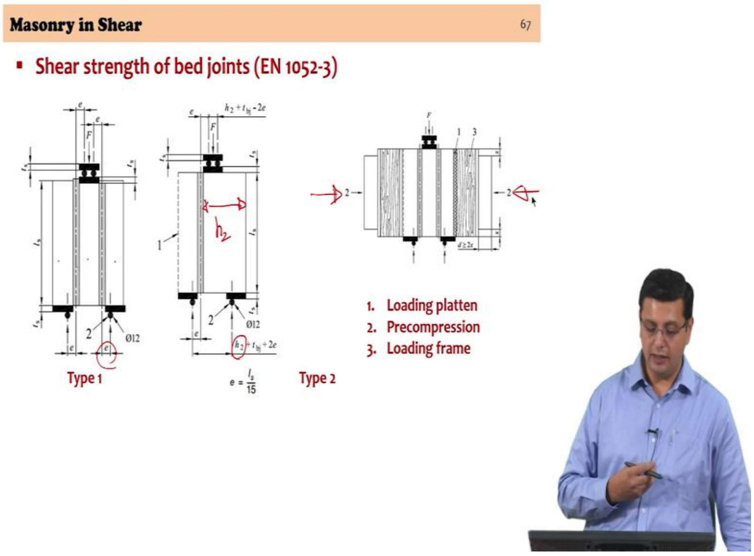

The second set of tests and i think it is important if you want to characterize the shear strength of the joint, you cannot use the test method that we just saw which is the diagonal tension test. So, we tend to use couplet test or triplet test the type of test that you have seen in the first slide. So, the shear strength of the bed joints; one of the codes that gives a test method and a protocol to conduct the test method is the European standards European norms 1052 part 3, and it does give you two different types of loading setups that you can use there is this type one setup where you are basically looking at a triplet arrangement there are three pieces of brick unit bonded by mortar.

So, in gray you see the mortar joints; the two mortar joints which are going to be subjected to the shear loading and the three pieces of brick unit is that is sitting with the mortar joints between them. And as you can see a double shear test setup is what we are going to be using, you can also introduce pre-compression to the joint in this case right.

So, if you look at the numbering here, you have the loading platen; the loading platen which is going to be applying the shear force you have the precompression in the walls and you have the overall loading frame which is holding the setup in position right. So, you have pre compression which is subjecting the block arrangement into a state that is expected in a wall. So, you have the masonry wall construction the joint has some precompression because of the superimposed loads and it is weight itself. So, you can replicate the precompression by deciding at what level you want to carry out this test. So, the precompression is provided to this sort of a setup and the test is carried out in a loading frame.

As you can see it is important to have control on the eccentricity of loading, if you can see both type 1 and in type 2, i will come to type 2 in a moment. If you look at type 1 you can see that it is important to have a limitation on the eccentricity of loading. Because if there is going to be significant distance between the line of action of force and the line of support you are going to have additional moments acting on the joint, you do not want that you want to try and minimize it. So, there are limit is on the eccentricity that is prescribed. So, the test has to be conducted with significant amount of care as far as the accuracy is concerned in the test setup itself.

A modified setup can be seen here where you are focusing on one joint instead of two joints as earlier and again there are prescriptions given as to what should be the size of the second unit and that is h_2; the size of the first unit is h_1 the size of the second unit is h_2. How do you arrive at the loading based on the intention to reduce the moment that can act on the joint itself. You want just shear to be acting on the on the joint that is being tested. So, this test is conducted under different precompression levels, because you want to characterize the behavior of the joint; this is affected by the level of precompression.

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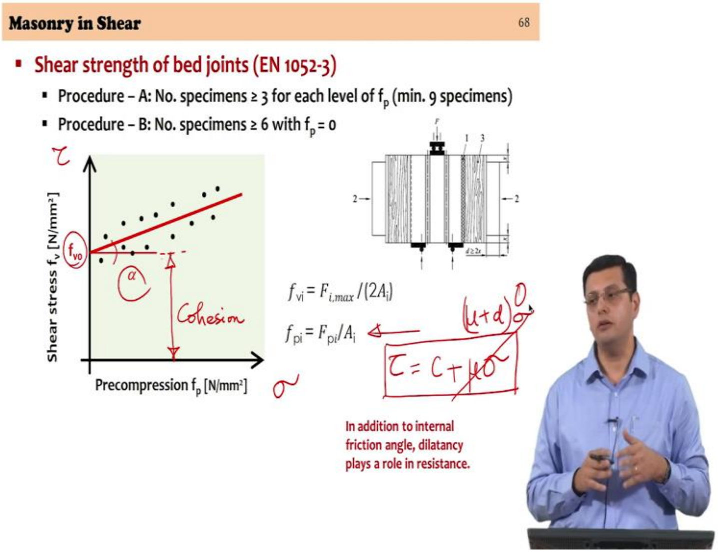

So, the way this test is conducted the code gives you a minimum number of samples that you must look at, you have it is expected that you look at for every level of precompression here denoted as fp that you have at least 3 specimens or more, right. And the repeatability of the test protocol and the outcome is the reason why you have a minimum number of samples that you must have in each of these levels.

And therefore, procedure would require that you look at least three levels of precompression and then you would have at least 9 specimens in all. You could also have another procedure where you are looking at six specimens and also include a state where there is no precompression; zero precompression. It is useful, in a moment you will understand why it is useful to do a test with zero precompression right. So, the way the test is conducted, let us say you have designated the different precompression levels you have zero precompression level as well. Since the test is being conducted in a vertical manner, you can theoretically have a situation of zero and practically have a situation of zero precompression.

And then if you can change the level of precompression you have designated levels at which the test is being conducted. The test is conducted, the failure stress is estimated you have the precompression level determined as the precompression force divided by the area of cross section whereas, the shear stress at failure as the force required for the joint to fail divided by since it is the double shear test you have two surfaces divided by

2Ai. And hence you will get several points at different precompression levels of f_{pi} and f_{vi} and that is then used to arrive at a best fit line which will determine what is the behavior of this masonry joint, the bond between the unit and the mortar itself. So, if you examine this graph here between the shear stress and the precompression, τ and σ right.

Now, the best fit line makes an angle with the horizontal and you have this value referred to as f_{v0} which is at zero precompression which is of importance. Two things are of importance- what is this angle, this angle is actually the internal friction angle of the joint and this value; which is the value of shear strength of the joint at zero precompression. This value physically if you look at this value, the only thing that is resisting the failure of the joint is the bond right; there is no precompression; there is no other resisting element here. So, what we are really looking at here is what is called cohesion which is nothing, but bond.

So, this y axis intercept is referred to as cohesion which is available because of the bond, if the bond strength is poor, if the bond between the masonry mortar and the unit is poor you will have very low value of cohesion. And then as precompression levels increase because of the internal friction angle which is again material dependent, you will have an additional component of resistance coming from precompression and frictional resistance.

So, the theoretical basis of such a test comes from an understanding of the failure as tau, the failure stress in shear as a combination of cohesion plus $\mu\sigma$, right. So, the shear strength of the joint comes from two components- cohesion © added to the friction coefficient (μ) into the precompression level (σ).

$$\tau = c + \mu\sigma$$
$$\mu = \tan\alpha$$

So, if you do not have precompression this goes to zero and then you have just the question, but if you have a crack initiated between the unit and the mortar there is no cohesion left and you have only the frictional component. So, you could have a situation where tau was equal to c plus mu sigma initially then the bond is lost C goes to 0, tau is then the residuals shear stress shear strength that you have in the masonry is nothing, but $\mu\sigma$. So, there will always be a residual shear strength as long as contact between the two surfaces is going to exist.

Of course, one aspect that I did not talk about here is alpha is referred to as the angle of internal friction; however, it is noticed that in materials such as masonry be it stone masonry or brick masonry as two surfaces slide there is a tendency for opening up of the joint when two surfaces slide, there is a tendency for the two surfaces to open up and that again how much it opens up it is because of crumbling of material on the surface and that causing a gap between the two surfaces that are in contact.

So, overall when you finish this sort of a test there is an increase in the volume that is noticed and that can be characterized as the dilatancy and the angle which a certain material assembly can give you. So, the second component mu into sigma; so, strictly speaking you should be able to characterize what is the dilatancy and what is the angle of internal friction to be able to understand the resistance offered by the joint itself.

With this, we have addressed the final aspect of the strength of the masonry assembly which was shear and we have looked at standard test protocols that can be used to characterize each of the properties from compression to tension. Particularly flexural tensile strength normal to the bed joint parallel to the bed joint and finally, shear in two situations shear strength of masonry and the shear strength of the joint. So, that brings us to the end of the second module which is on the strengths of the materials that constitute the masonry and the behavior of the assembly itself.