Design of Masonry Structures
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Module - 05
Lecture - 38
Special Topics – Assessment of Existing Masonry Structures

Good morning, we will look at the last of the topics for this course and that is one of the Special Topics, the third of the special topics which will focus on Assessment of Existing Buildings; Existing Masonry Structures. And the key reason for looking at assessment of existing masonry structures is primarily the very large stock of existing masonry structures that a country like India has; that while there may be opportunities for design of masonry structures in your career as a structural engineer, very often you might encounter the problem of structural assessment, retrofit, extension of masonry buildings which are existing facilities. And therefore, in the next three lectures including today's, we will look at a basic framework for structural assessment; a quantitative approach to structural assessment of existing masonry structures.

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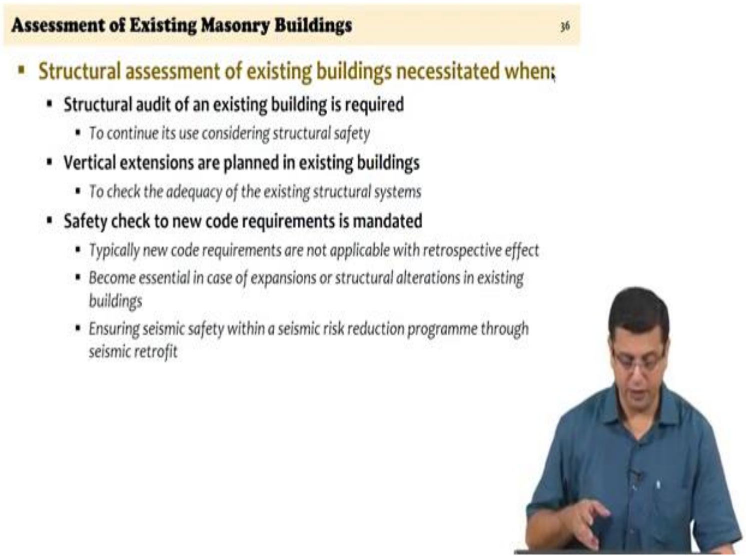

So, when does an existing building require structural assessment? This can be necessitated due to different situations. Typically, we are looking at when an existing building requires a structural audit to be performed right. It may be because of a new tenant moving into the building, going to take over the building as a licensee; that a company requires that the safety audit of a building be carried out.

So, when a structural audit is required it is essential that a quantitative structural assessment of the existing building particularly its structural safety considering the use to which it is being, its proposed use and also the existing loads as per the codes that are in rigor.

So, often you will be called to do a structural assessment in the context of doing an audit; a structural audit of an existing building. And here the focus is primarily on structural safety, you are establishing if the existing facility given the number of years it has already been in service, does it have the essential structural safety to be put to use for a new purpose or for continuing the use of the building itself.

There are several situations where existing infrastructure, this is the second situation where I would think structural assessment becomes fundamental, when an existing infrastructure is being extended. These could here the reference is primarily to vertical extensions, when you are doing lateral expansions, when you are doing horizontal expansions typically, we would going for a construction joint and ensure that the old structure and the new structure do not directly interact with each other.

And, there are requirements of how much gap you must actually leave and what detailing you must do between an old part and the new expansion in the structure. Whereas, when you have vertical extensions of existing buildings, then you would have to check quantitatively the adequacy of the existing structural system for the new loads that you are going to design this structure for.

So, the second situation would be when you have vertical expansions and adequacy of the existing structural system would have to be checked. The third situation is often encountered again, is when safety check is required to a new core dual requirement, right. A classical example that I can give you is a city like Chennai, which was till 2002 in seismic zone 2, moves in 2002 to seismic zone 3. Which would mean that the earthquake demand prescribed by the code is now different, seismic zone 2 as per the original code requirement pre 2002 for zone 2 you do not have to do a seismic design, but, was zone 3 seismic design is mandatory.

So, you are looking at existing buildings which have been designed in the pre 2002 regime where seismic design might not have been addressed at all. So, these are all gravity frames, therefore these buildings would actually fall short of requirements of earthquake safety. Now, that is true for public buildings and that is true for private buildings. So, it starts becoming the prerogative of the public authorities or the private owners to want to ensure compliance of the existing facility to the new code requirement.

For public buildings it is the responsibility of the government to ensure that important public facilities- schools, public buildings are all catering to the new code requirements and therefore, it might require some strengthening and retrofit. So, that is the third situation in which you are going to require a quantitative structural audit. It is very rarely that code, particularly structural codes would require that the code prescriptions are applicable retrospectively. It very rarely happens and it is not something that is practically feasible that you go and fix all existing buildings which have not been designed as per code requirements to the new code prescription.

So, this is typically not done, but when you are looking at structural safety it might so happen that to ensure particularly seismic safety you might have to do some retrofit of existing masonry structures and that would depend on existing retrofit programs in the country; in the territory.

Now, an important point to note is while codes do not require compliance of existing buildings to new coded regulations, if the building is not undergoing any alteration. When, a building is going through structural alterations in the horizontal plane or in the vertical plane with additional floors being added. There is a requirement that the new building that is whatever is the altered building complies with the new coded requirements.

So, whenever there is alteration there is a requirement that you comply with the new codal requirements though the existing building might have been constructed in the pre codal regime. So, this is something that you must keep in mind. So, particularly when it comes to safety checks for seismic safety checks public facilities, existing facilities may fall short of basic requirements of seismic safety. And, within earthquake risk reduction programs they may be a retrofit program of identifying, what are the vulnerabilities and how can you overcome the vulnerabilities by strengthening and retrofitting the structures.

So, this is the third situation in which a third of structural assessment becomes required. So, it is within this context that we are going to be talking about. The focus as I said even earlier is primarily on seismic safety because life safety matters and very often masonry constructions, unreinforced masonry constructions as we have seen unless there are specific earthquake resistant features built in, do not have seismic safety.

So, the importance of structural assessment in our last set of lectures within the special topics is focused on seismic assessment, is focused on achieving seismic safety in existing buildings.

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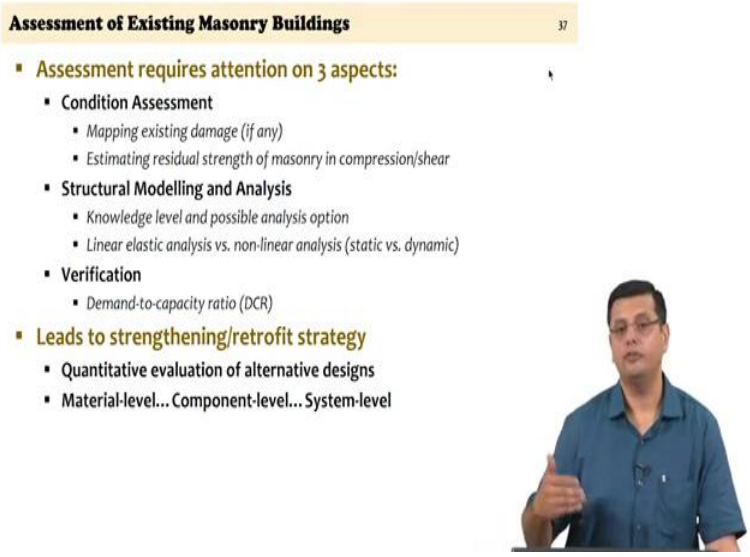

Let us say you have one of these situations, let us say you are looking at verifying the seismic safety of an existing masonry construction. Focus is typically paid to 3 aspects within assessment. The first stage is called condition assessment; since you are looking at a building or an infrastructure that has been in service for a number of years before your intervention.

So, the first stage is called condition assessment, where you would try to prepare or get the drawings of the building and then on the drawings of the building map what is the condition of the structure, is there existing damage? If there is existing damage, that must go into any repair and strengthening program that you are going to be proposing for the structure.

And more importantly, what becomes important is to understand, what is the residual strength of the masonry that you are looking at right. So this condition assessment is one on one hand trying to map, if there is any existing damage which you should take care of to ensure that the structural health is not compromised; structural health of the building is not compromised. The second aspect that you have to look at, since a quantitative structural assessment is being carried out you need to know what is the residual strength of the masonry in the structure.

When you design as a designer you are free to choose the design strength of the structure, but when you are looking at assessment of existing buildings, this is not something that is in your hand. The existing strength of the structure, strength of the structural materials is something that you should be able to assess, evaluate and use in your structural assessment. So, the first part is condition assessment.

Today, we will focus on this aspect of estimating the residual strength in particularly in compression and then we will also examine shear. The second aspect is if you have to make a quantitative check, you must have a model for the structure this can be a simple model based on hand calculations, it could be a complex model where you are using finite element methods or any other appropriate method. And then carry out an analysis, be gravity load analysis or a dynamic analysis considering, lateral forces.

So, you require structural modeling and analysis, but here an important aspect that one must keep in mind is the type of analysis that you choose. The level of intricacy the complexity of the analysis that you choose must be commensurate with the knowledge level on the structure that you have. In the sense that if you have a thorough knowledge on the structure, its materials, the strengths of it is materials the dimensions of all the structural members, then the knowledge level that you have on the existing structure is rather high. When the knowledge level is rather high, uncertainties are reducing and therefore, you can adopt complex analysis methods.

So, if you want to adopt a non-linear finite element analysis approach, you cannot be in a situation where you do not have information on the structure, you cannot use a complex sophisticated analysis technique, when the level of knowledge on the structure is very low, this is not commensurate. You have high uncertainties as far as the geometry and material is concerned, but you are using a very sophisticated analysis technique, this is not commensurate.

So, if you want to use a sophisticated analysis technique the knowledge level must be much higher, you must make an attempt to get more information on the geometry verify the structural system, dimensions get residual strengths of the material as much as possible. Then, you have a better knowledge level on the structure, on the structural system, on the structural materials uncertainties are reducing, then you can adopt a highly sophisticated highly complex analysis method or analysis platform.

Let us say knowledge level is low; you are not able to get adequate information on the structural geometry, adequate information on the structural strengths keep the analysis as simple as possible, then it is commensurate. So, knowledge level with the choice of analysis option must be consistent. This is an important point that needs to be communicated.

Few codes today address this aspect and permit certain types of analysis based on the knowledge level you have on the structure. The eurocodes for example, and the FEMA standards require that you classify into which knowledge level you would fall and then adopt the allowable options for analysis and modeling and analysis within that level of knowledge.

And therefore, you will have to make some decisions when you are doing structural modeling and analysis, am I going to be using a linear static analysis, am I going to use a linear elastic model, am I going to use a non-linear analysis tool or non-linear analysis method, am I going to be happy with static analysis or should I do dynamic analysis. There are different decisions that one would have to take, when it comes to the modeling and analysis, and this is linked to how much information you know or have about the structure.

The third aspect, is you have done your condition assessment, you have got your residual strengths you have carried out an analysis for different loads. Let us say you are talking of a public building sitting in a newly classified earthquake zone, you are doing a seismic verification, you have actually carried out a seismic analysis on the model of the structure. Now, you need to verify whether the structure has adequate earthquake capacity.

So, the last stage is actually the verification, now what you are doing is, you are checking what is the demand or capacity ratio available in the structure, at the structure level at the different component level you are trying to add identify, is this demand to capacity ratio favorable. Are we seeing situations where demand is higher than the capacity of different components that is when you will be able to establish a strengthening or a retrofit strategy you know which elements are weak, which elements need strengthening, which elements needs stiffening and this leads to a strengthening or retrofit strategy.

And therefore, you are looking at a quantitative approach to arriving at the strengthening strategy. This quantitative approach is also useful depending on the weaknesses you have identified in the structure, you can evaluate one design versus another design, alternative designs of strengthening and retrofit based on quantitative approaches. Are you able to achieve with a certain type of intervention a better demand to capacity ratio and economical design or do you have another alternative which you could use for achieving the same goals.

And when you are looking at strengthening and retrofit strategy we are really talking about you might have to improve the quality of the material if you can; grouting that is typically done is to improve the strength of the material locally at the material level. You might have to strengthen walls, beams, columns they are really working at the component level, structural component level. And then finally, you might have to tie up the entire structure and masonry we have seen the importance of making the structural walls work together.

The earthquake design requirements, the earthquake design and detailing requirements mandate that you must have lintel bands, you must have plinth bands, you must have roof bands and these are basically, at the system level trying to hold the entire structure together and ensure integral action against earthquakes, so that is at the system level.

So, you would have to look at your strengthening strategy or the retrofit strategy both at three different levels, at the material level, at the component level and at the system level. And therefore, assessment is the quantitative pathway that leads you to this goal of achieving risk reduction by intervening on a structure which is identified to be vulnerable, ok.

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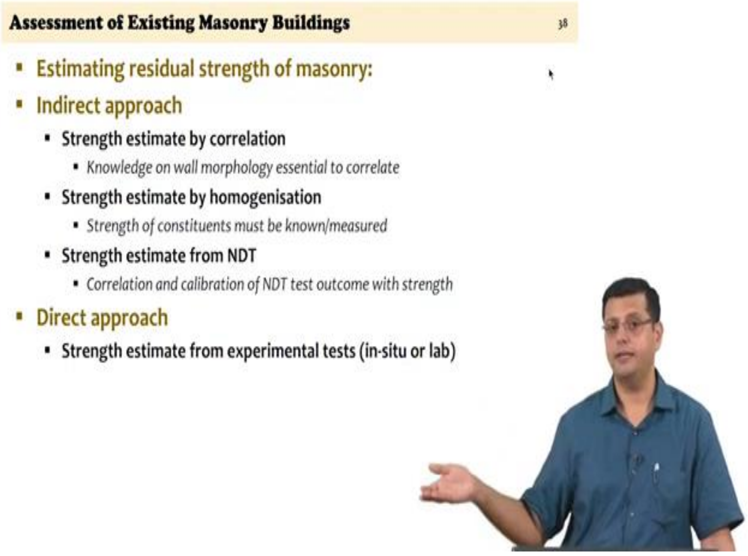

So, as I said I would like to focus on this aspect of estimation of residual strength of masonry today. So, condition mapping as I said earlier would require that you get drawings of the structure and then start marking what are the damages that you might notice are there, cracks are there, loss of cross sections, all that is mapped and that is a an initial documentation that you would do. The second aspect is coming and estimating the residual strength of masonry. Because very often, the important query that comes to anyone's mind is does the structure that you are working on have sufficient strength in terms of its structural materials to resist the combination of loads that is expected to be serviceable against.

So, as far as your residual strength estimation for masonry, I would classify approaches as indirect approaches and direct approaches, ok. And what are these indirect approaches that I am talking about. In the indirect approach have one first possibility of estimating the strength it is an estimate, it is an you are estimating what could be the residual strength, but by correlation. That you really do not know exactly what the strength is or you do not have the means of going in identifying what the strength of the material in the existing structure is. This could be limitations of resources, financial, time and several others or sometimes the structures that you are working on are so important that you cannot want you can go and say I need to take some material out of the structure it might just not be permitted.

So, in such situations where due to resource crunch/ time crunch you are not able to get actual strength from the structure that you are working on you can work by correlation, but to work by correlation you need to know you need to have information and knowledge on the typology of the materials that are there in the structure. You need to have knowledge on what is called wall morphology; you need to know what the structural load-bearing walls are made out of, and then you have some basis to correlate, we will examine that in a moment.

The second method is by homogenization right, we have seen homogenization of masonry strengths earlier on in the course, where you know that if you know the strength of the mortar and if you know the strength of the unit you can in a way arrive at the strength of the masonry assembly, right.

So, you might not be able to directly estimate what is the strength of the masonry, but if there is a way of knowing what is the strength of the mortar and strength of the unit, there are methods of arriving at a homogenized strength of masonry. But, here the strength of the constituents has to be known, you should have some basis for arriving at the strength of the constituents in the actual structure.

The third is something which is probably the weakest and it is better that we do not adopt that approach and I will in a moment tell you why you should be careful about that third technique, which is strength estimate for nondestructive testing. In fact, that phrase itself is not appropriate because you cannot estimate strength from non-destructive testing.

So, if you were to depend on nondestructive testing and arrive at strength estimates you are only looking at correlations and calibrations and you will not get a direct strength. So, that is why you find this non-destructive testing, strength estimates sitting under the indirect approach, ok. Here correlation and calibration of the non-destructive test and the possible strengths; that correlation is essential and you have to calibrate the non destructive test outcomes with actual strength test. So, it is a rather involved way of arriving at the strength estimate.

But please remember, I have placed it under an indirect approach, we will discuss this in a little detail in a moment. The final approach, probably the most appropriate approach is the direct approach where you are in a position to do in-situ or laboratory tests on extracted specimens and you make strength estimates from these extracted specimens by carrying out experiments.

Of course, the question will be how many such samples will I be able to take from a building, should I be taking it from a certain part of the building or representatively from all parts of a building. There are several questions that you as an engineer will be faced with in that sort of a situation, but if there is a possibility of extracting material and testing it in a laboratory or carrying out a test in situ that is the best option that is available to you.

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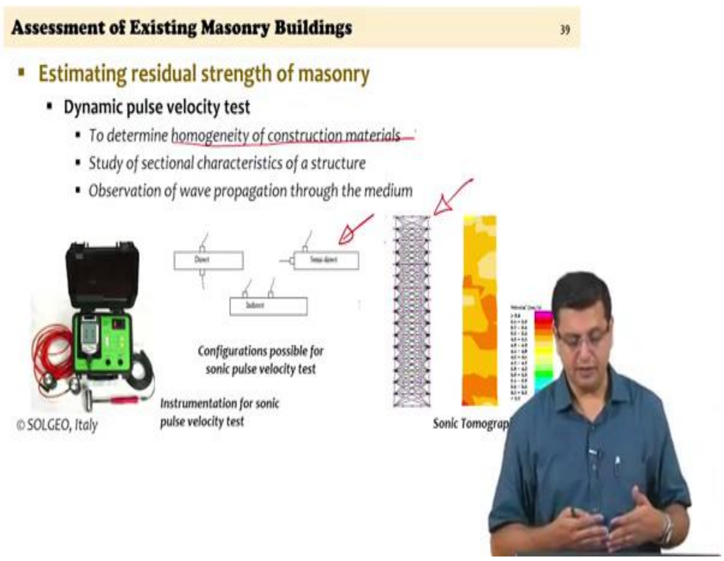

So, we will examine some of these, I would like to look at the issue of non-destructive testing to start with because I would like to exclude it as much as possible. It is a useful technique, it is a very powerful technique, but not for strength estimates and that is something I would like you to carry home as a message. So, pulse velocity tests are typically done for concrete as well; as you know you do this ultrasonic pulse velocity test UPV test, we are talking about the same technique the dynamic pulse velocity test dynamic because you are creating an impact and waves that are generated by impact.

So, it is actually dynamic pulse velocity test that we are talking about and instrumentation is typically simple for a dynamic pulse velocity test, you need a transmitter of sound because sonic waves are being transmitted; you need a receiver of sound. And then you are basically estimating how much time is the pulse taking to go from one end of the specimen that is being tested to the other end of the specimen, and then based on the distance which is nothing, but the cross sectional dimension that are arriving at what the velocities are.

If you remember from ultrasonic pulse velocity tests used in concrete, once you establish what the velocity of the primary wave p wave is you basically classify whether that is good quality concrete, moderate quality concrete or poor quality or doubtful quality of concrete. Now, that is really all that you can do with non-destructive testing such as pulse velocity test.

You will know, you will have some information on the quality of the masonry not quantitative strength. If you need quantitative strength what you should actually be doing is take a certain typology, do a actual compression test, carry out non-destructive testing using pulse velocity on that specimen and arrive at a correlation, and then use it for the rest of the structure. That means, it is a really involving and depends on several other parameters which you should be in control of as far as a test like this is concerned.

So, basically this is a powerful technique if you were to use pulse velocity test to understand the homogeneity of the construction materials, right. An existing structure might have been constructed at different times might undergo different levels of deterioration in different parts of the structure; such a technique can be quickly used to arrive at whether or not there is homogeneity in the construction materials.

So, you could do these pulse velocity tests on different parts of a wall and different walls in a structure and arrive at whether or not you see homogeneity in the structure. If there is lot of heterogeneity in the velocities through these structural load-bearing walls, it starts giving you a basis that some parts have been affected due to aging and some parts have been are in better conservation, better state of preservation. And this will start giving you a basis for some strength values that you must use in a reduced manner in some parts in a way that is not reduced in other parts, where deterioration has not actually happened.

And therefore, if you are studying a wall cross section you are really trying to understand since the wave velocity is directly proportional to the density of the material, you are getting an information on the cross sectional property of the wall or the material that is being studied. And basically, if you want to further elaborate on these tests one can take the waves that come out, receive at the receiver, and you can carry out your wave propagation studies on that and basically you are characterizing the medium.

A little more involved way of doing this as you know in a pulse velocity test, you could either have the receiver and transmitter placed on two sides of the wall, we call that the direct measurement. But, if the opposite sides of the wall are not accessible you might want to go in for the semi direct measurement where the transmitter and receiver are on two adjacent sides of a wall. And, you can even do an indirect measurement which is the three other sides or two the opposite side is inaccessible and you can use the receiver and transmitter on the same side.

However, in all these you are actually looking at wave travel from the transmitter to the receiver and a single array; a single array going from the transmitter to the receiver. You can use dynamic pulse velocity test in a more efficient, but more cumbersome manner where you can create an array as you see in this test here, I have transmitter points on one side, I have receiver points on the other side. And I can look at multiple arrays which means I get a lot more information on the cross section and I can use all that information and with the use of algorithms it is possible to arrive at a contour of velocities of the cross section.

So, this is a much more involved technique it is referred to as tomography; sonic tomography, because sound waves are used to study a slice which is a tomo and here you are getting a contour of velocities. And as I said with a contour of velocities like this, I am not able to arrive at strengths, I still will only be able to understand if there is homogeneity in the construction material in the cross section that I am studying. If there is let us take a brick wall and a brick wall has parts where the velocity is really low and parts where the velocity is significantly high; it means that there is loss of material leading to reduced density in some portions and it necessitates grouting in that location.

So, I am getting a qualitative information from such a test, it can help me decide a certain intervention like grouting to strengthen and improve the quality of the material in the masonry wall. So, it is a very powerful technique, but as long as you understand what it can be used for, it cannot be directly used for strength.

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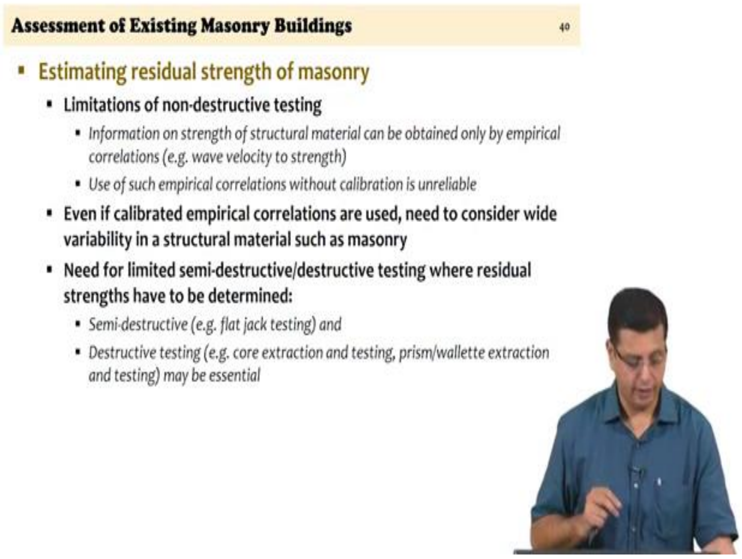

So, important limitations of non-destructive testing is that strength information is possible only if you correlate empirically with wave velocity. Another test which is a non-destructive test that all of you would be aware of is the rebound hammer or the Schmidt hammer test that you use for the concrete. The rebound hammer test or the Schmidt test actually gives you the hardness, the surface hardness of concrete. It does not give you the compressive strength of concrete, you arrive at the compressive strength of concrete by calibration of that surface hardness with the compressive strength of concrete itself.

So, this non-destructive test, most all non destructive testing techniques, if you want to derive strengths you need to be able to calibrate and you will get empirical correlations because material to material those correlations will vary. So, this is something which is of an important limitation and if you were to use charts that are available with the instrument, without correlating it to the type of material that you are looking at, your correlations the calibration values can be unreliable.

So, strength estimates from non-destructive testing is a red flag. So, it is very involved and we have a lot of variability even if you are going to be using calibration using empirical correlations. The variability in a material like masonry something that we have always seen. If you remember the initial lecture, we looked at the kind of variability in the modulus of elasticity from the compressive strength that you can get in brick masonry and concrete block masonry.

So, we are looking at a material which is rather strongly affected by uncertainty in a material like that if you are going to calibrate for one type of masonry it may not be valid for another type of masonry. Let us say you are using fly-ash bricks with cement versus clay bricks with cement these are different as far as the way velocities are going to be through the cross section.

So, variability in masonry something that you want to keep in mind even if you want look at calibrating empirical coefficients. Therefore, when you are not left with this option of non destructive testing for strength estimates what do you do, you have to make recourse to semi destructive testing or destructive testing to arrive at residual strengths.

So, there are some tests; one of the tests that we will be looking at is called the flat jack testing which is the semi destructive test. You could also do something else which is you can extract material from the structure which is rather invasive, but in some cases it is possible that this works you can extract a core, you can extract a prism and a small wallete and test it in a laboratory and you will be able to get the residual strength. So, this is something that we need to look at a little bit in detail because there are some do's and don'ts clearly as far as semi destructive and destructive tests are concerned.

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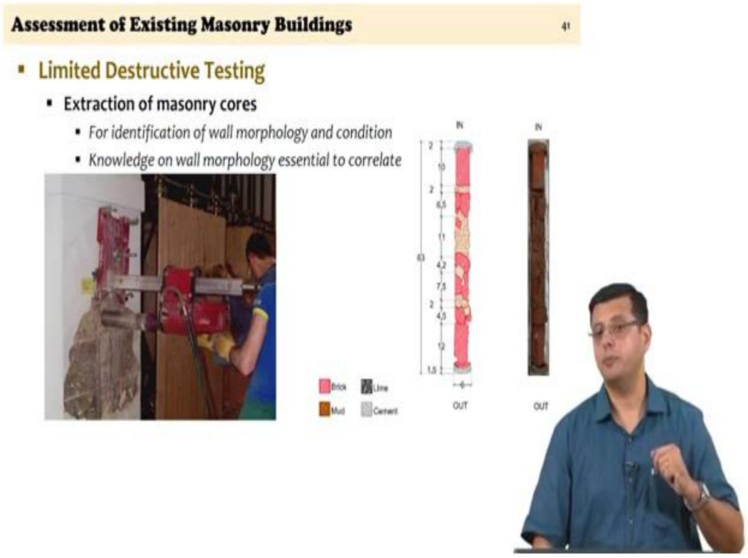

Now, let us say we are going to do some limited destructive testing in a structure, how can we go about it. Let us say you are allowed to do only limited destructive testing in the structure that you are working on. With that information, how will I will be able to arrive at some residual strength, my aim is very clear, I need to do a quantitative structural assessment; I need strengths, I need to be able to arrive at that from the situation of the structure.

Let us say you extract masonry cores; have you seen extraction of cores from concrete structures that is something that is done quite often? You have a core extraction machine which is fixed on to the structure, structural member and then a core is drilled out. You can take this core examine it in the field you can take it to a laboratory and do tests on it or on you can make it disintegrate and then do a test on it is constituents also. So, you can do a lot of tests with cores.

Now, we need to speak about masonry cores for a few minutes; what we could do is if you were to extract a core, it gives you a good information on what the unit is, what the binding material is the mortar is and what is the condition of these two constituents of masonry. So, it helps in establishing what is the morphology of the masonry and what are the, what is the condition of the material where you have extracted it from.

Now, why is it essential to understand the wall morphology? Most often walls are plastered; you have no idea of what the type of unit, size of unit, quality of unit what is the mortar what is the type of mortar and what is the condition of the mortar sitting within the wall cross section. An extracted core can help you establish one what is the wall morphology, is it brick masonry with lime mortar, is it brick masonry with a lime plus cement mortar or is it brick masonry with cement mortar or is it a concrete block masonry construction is it any other type of unit or mortar constituent.

So, it helps you establish what is the morphology of the cross section and then you can also look at the condition of the masonry, condition of the units and condition of the mortar. This knowledge on the wall morphology is essential for correlation. So, the first method that I talked about under the indirect approaches. Once, I know what morphology of material I am looking at in the structure that I am going to study, I can by correlation establish what may be the ranges of strength from literature. So, for that you need to have some information on the wall morphology.

So, let us say you have to do this what can you do; this involves extraction of material from the wall from the load bearing walls you would decide how many are possible, you would decide which locations, you would like to get this done from. It is quite cumbersome, but can be done, and you can decide on what sizes of cores you want to extract and what depth of core you want to extract.

Once the core is extracted it is possible if you carry it out in a systematic manner you know from what depth you are getting what material. It is possible to reconstruct and understand what is the cross-sectional morphology of the wall that you are looking at, then you know what typology of masonry this is and then that information is extremely crucial.

What you are seeing here is a wall cross section coming from a historical structure, it is a structure which is 180 years old. But a formal masonry construction where the use of mud mortar and the use of lime mortar has been there. So, it is important to know information of the cross section and extraction of a masonry core can help you arrive at that.

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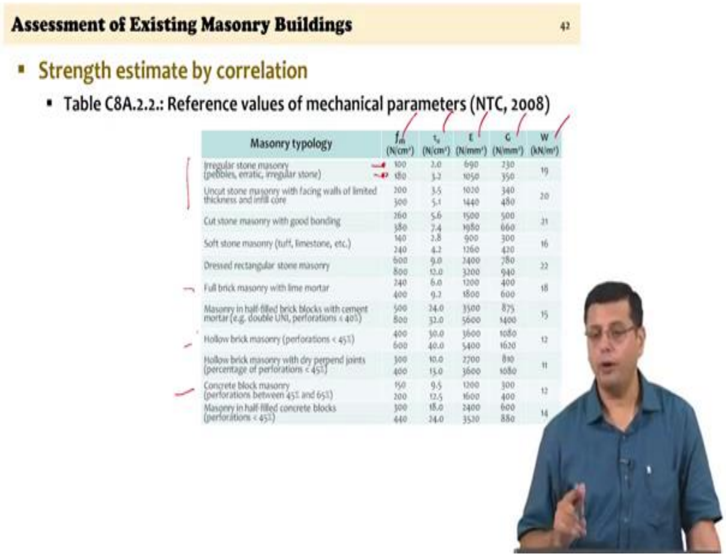

Once you do that then you know what is the typology of masonry you are examining. Now since it is understood worldwide that you cannot go and do tests on existing structures all the time. There are certain codes which have established a range of mechanical parameters, typology wise based on extensive databases collected over time which can be a useful resource for you to establish what may be lower bound and upper bound strengths of a certain typology of masonry, right.

So, I am making reference here to the building code; it is called the building norms technical norms for buildings, for constructions, the Italian building norms and you have tables like this which based on the masonry typology will give you compressive strength upper bound, lower bound compressive strength.

So, as you can see there is a lower bound strength and an upper bound strength, the shear strength, the modulus of elasticity, the shear modulus and the density of the material itself. So, depending on your understanding of what morphology of construction you are seeing you can then look at lower bound estimate an upper bound estimate of those strengths.

And you can work now with a lower bound estimate and an upper bound estimate right, you do not have to work with one value that is coming out of the structure, but you have a range of results. So, you can do a factor of safety check lower bound value, factor of safety check upper bound value and you have a quantitative scientific basis to establish safety in the structure itself.

So, you can look at the different typologies here; of course, there are historical masonry constructions the first few are all irregular stone and uncut stone and all that. But, you can also see if you have full brick masonry with lime mortar you have hollow bricks, you have concrete block masonry, you have masonry with cement and brick masonry with cement. So, you have an information an important resource here with which you can actually establish as I said lower bound and upper bound estimates of compressive strength, shear strength modulus of elasticity shear modulus and density which is sufficient from most of your calculations.

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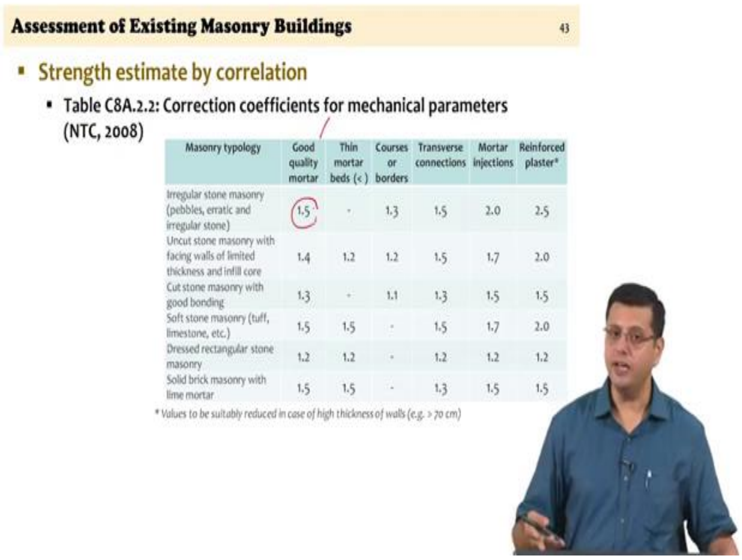

Masonry typology	Good quality mortar	Thin mortar beds (<)	Courses or borders	Transverse connections	Mortar injections	Reinforced plaster*
Irregular stone masonry (pebbles, erratic and irregular stone)	1.5	-	1.3	1.5	2.0	2.5
Uncut stone masonry with facing walls of limited thickness and infill core	1.4	1.2	1.2	1.5	1.7	2.0
Cut stone masonry with good bonding	1.3	-	1.1	1.3	1.5	1.5
Soft stone masonry (tuff, limestone, etc.)	1.5	1.5	-	1.5	1.7	2.0
Dressed rectangular stone masonry	1.2	1.2	-	1.2	1.2	1.2
Solid brick masonry with lime mortar	1.5	1.5	-	1.3	1.5	1.5

* Values to be suitably reduced in case of high thickness of walls (e.g. > 70 cm)

This is also supplemented by correction coefficients; this same code also gives you correction coefficients. Let us say you have identified the morphology, but then when you extracted a core you found that the quality of the mortar is very good or the quality of the mortar is so bad, that you are uncomfortable using just the upper bound, lower bound strengths mentioned in the previous table without any reference to what is the quality of the mortar joint; we have seen that this the mortar joint has a very important role to play in the strength of masonry.

So, if based on your observations on the structure from the extracted masonry cores, you are able to establish are you looking at a good quality mortar joint, are you looking at a poor mortar joint then you can actually use correction factors to improve the values that you saw in the previous slide.

So, let us say I have done this test I find that the mortar is average it is poor it is nothing that is holding the structure in the location so well together, then I continue to use the factors that are there in the values that are there in the previous table. But, then if I see that the quality of mortar is really good then I can actually increase those values by a factor; for example, 1.5 multiplied by the lower bound and the upper bound values in the previous slide.

And then of course, you can see there are many other possibilities here, if it is grouted, if it has some plaster which is got some reinforcement there are different values that you can use and these have been calibrated against experimental tests. So, it is an important resource which one can feed into in the absence of actual strength estimates from the structure that you are working in, but knowledge on the morphology of the structure is extremely important.

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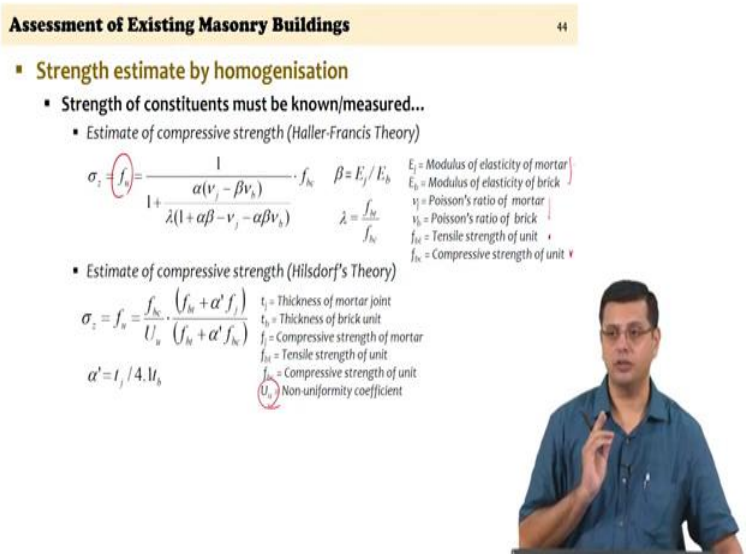

By homogenization, strength estimate by homogenization here it is essential that we understand the strengths of the constituents that we are using, ok. So, it might be possible that you are not able to take an entire wallete to test in a laboratory, but you are able to take some amount of mortar you are able to take some brick units and have some estimate of the strength of this constituents. And, with the estimate of the strengths of the constituents we have seen that you can arrive at the compressive strength of the material, we have seen different theories that you can use to arrive at the compressive strength of material from it is constituents.

The example that I can give you here is the Haller-Francis theory that we have seen earlier, the Hilsdorf’s theory that we have seen earlier where the modulus of elasticity of the mortar, modulus of elasticity of the brick, poissons ratio of the constituents and tensile strength of the unit and the compressive strength of the unit known, you will be able to establish what is the failure strength of the masonry in compression.

So, and this will basically depend on the geometry thickness of the mortar joint and the size of the unit as well. So, homogenization is possible there are established theories we have also seen the Hilsdorf’s theory, where there is an additional constituent- the non-uniformity coefficient depending on the type of masonry that you are looking at. So, homogenization is another approach that you can adopt, but constituent strengths are essential and then you can arrive at what is the compressive strength of the masonry itself in your residual strength calculations, ok.

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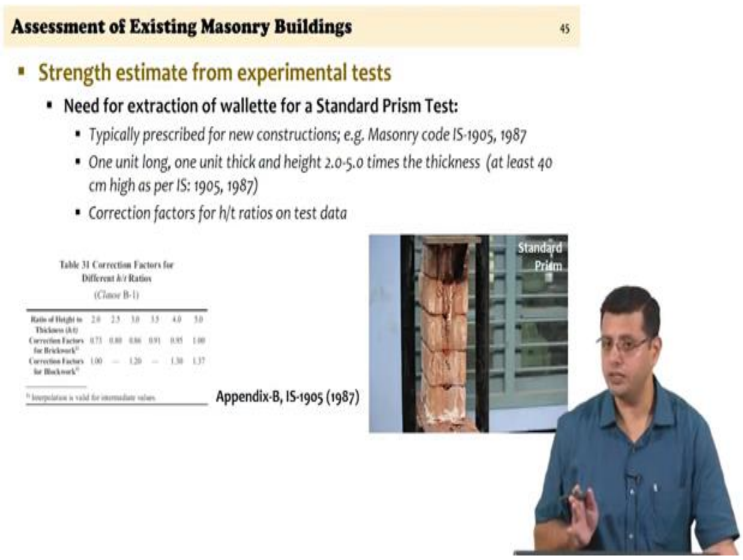

The third is from strength estimates from experimental tests. So, what experimental tests can be done and how would you go about it and there are two things that I am focusing on. One is the masonry core, can I take the masonry core and claim that I will be able to do a strength test on the masonry core and the second thing is this flat jack test that I mentioned a few moments earlier. So, strictly speaking for a new construction you are required to look at a prism test, right.

So, you need to, we have seen how the basic compressive strength can be arrived that you make a prism get the compressive strength and then to get the basic compressive stress you take 25 percent of the basic compressive strength, of the compressive strength coming from the test and then you use it for a permissible stress design. So, you need a standard prism, you need a standard prism now when you are working on an existing structure does that mean extracting a standard prism from the structure.

Second question, can you get a standard prism from the existing structure? A standard prism is made by stacking one brick over another and having about 5 or six bricks in one stack right, but when you construct a structure it depends on the bond that you adopt for the wall cross section. So, you are not going to get a stack of bricks from the structure itself you will have to extract a wallette. A small wallette from the structure to be able to conduct anything that is like a standard prism test to establish the compressive strength of masonry itself.

So, the Indian codes, many other codes internationally also are silent on this if you know it only says if you actually have to establish the compressive strength of the masonry then you have to adopt techniques similar to what could be adopted for a new construction what does that mean for a new construction you would make a standard prism, for an existing construction go get something comparable to a standard prism from the structure that is easier said than done.

So, this is what the code would say make a standard prism, do a compression test and based on h by t ratios that you are aware of; for example, appendix-B of 1905 would give you these correction factors you can use the correction factors and arrive at the compressive strength for brickwork or block work. So, clearly these are prescribed for new constructions right and as I said we normally go for one unit and 5 or 6 of them placed one on top of the other, stack bonded and use the correction factors itself.

So, can this be a basis for us, yes it can be a basis for us, but one has to be careful about what we are getting and how we go about doing it.

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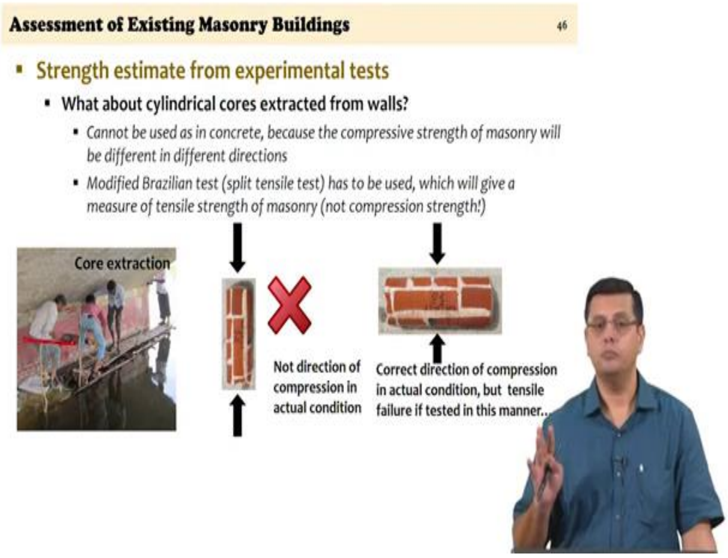

Well, a few moments earlier we were talking about extracting a core from a masonry wall. Can I use the core to arrive at the strength? That is what we typically do for reinforced concrete structures; we would extract a core and then do a compression test on the core and use the compressive strength coming from core tests. Possibly take three cores at three different locations get an average compressive strength and that becomes a compressive strength, that I can use for the concrete in the structure and this is coming from the cylindrical cores extracted from the structure. Can that be applied to walls is the first question.

There is a problem here a or significant problem here and one has to be conscious of this. Let us say you extract a core from a structure; you see a picture here from a historical masonry arch bridge and core is being extracted from the piers of this 180-185 year old masonry arch bridge not very far from here in Pondicherry and this is brick and lime.

So, you see a core is being extracted; now, what do we do with the core? I can examine the core understand the morphology and say it is brick good quality brick and good quality lime and use correlation, but if I were to use the core for strength what are the precautions. It cannot be used as we would use in concrete because you know that the compressive strength of masonry is going to be different depending on the direction that you test it in yes, there is a correlation to the direction of the bed joint.

So, if one way to look at extracting this core taking it to a laboratory and then conducting a compression test on the cylinder extracted, then you would realize that the direction of loading with respect to the bed joints is 90 degrees different to what the actual structure is subjected to, would agree with me. The core has been extracted in this direction, the bed joints are in that direction the bed joints are now perpendicular to the direction of compression and then I take this to a laboratory. But to test a cylinder in a universal testing machine I need to put it the other way around and now the direction of loading is different to the bed joints.

So, question is what compressive strength do I get? Is this compressive strength the true compressive strength that I need to use depending on the direction of the bed joint itself. Answer is no, you cannot; what else can I do, if I want to maintain the directionality of the bed joints then I should not be testing it in this manner, I should be testing it in the other manner, right. I should be testing it like the bed joint is with respect to the compression loading itself, but if you do that what you are actually doing is called a modified Brazilian test or a split tension test.

And, what does that give you, it gives you the tensile strength of the material you wanted the compressive strength, you get the tensile strength again you are going to be you have taken material from the structure, but you are getting tensile strength you will have to make some correlation to arrive at what the compressive strength is. So, uncertainty over uncertainty; you are really not making use of good material that you have actually got from the structure. So, this is a fundamental problem. So, if one way to blindly use extracted cores and get compressive strengths out of masonry constructions beware of the compressive strengths that are being used for structural assessment.

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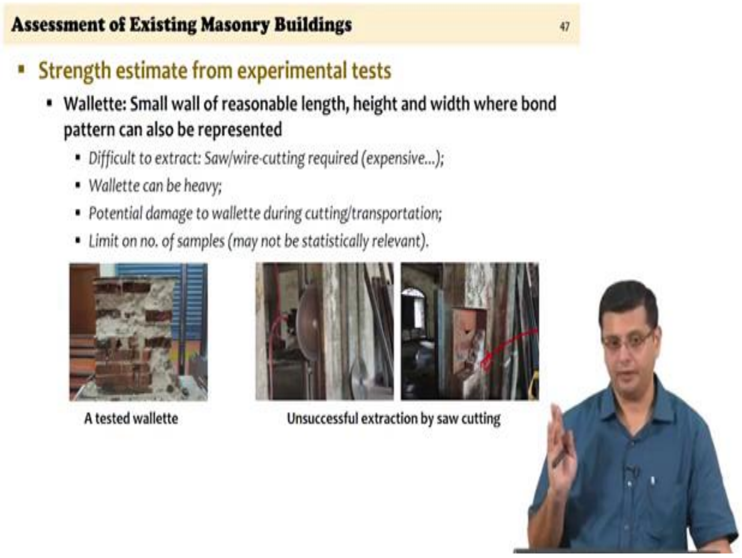

What else can you do, you actually have to extract a wallette then because that is what the code silently says extract something that is comparable to what a prism is for a new construction. But, you cannot extract a prism because of the bonding therefore, you extract a wallet which is a small wall. Now, do you have prescriptions on what dimensions these should be, yes there are some prescriptions, there are at least two codes internationally that give you an idea of what these can be, but there are significant problems here.

So, we are looking at a small wall of reasonable length, height and width such that it is representative of the masonry that you are looking at, the bond pattern also will become representative depending on where you extract the masonry wallette. But, this is not that easy to execute, if you take a small wallet you should be able to handle it this is going to be quite heavy as well.

So, you have issues one it is difficult to extract, basically you will have to cut it and as you see the picture on the bottom, right you can see that you will have to slice the wall you will have to cut it at the top at the bottom at the side and then extract it, right. So, it is in it is rather involving a lot of in machinery is required and I am not over-emphasizing, but it is really expensive to get two or three such wallettes extracted from a structure. And the other question is if it is an old building you are also worried if you are going to damage the structure in the process of extracting.

One fundamental problem is in the process of extracting there are vibrations; the wallet itself can get damaged; the picture that you see here, you can see the part of the wallet has refused to come out and then all the effort that you have taken to extract one prism is gone. The wallettes can be heavy, you need to handle it carefully one man cannot handle it one person cannot handle it you actually have protocols for how this has to be fitted confined within a cage, within a timber box, if possible. If you want to transport it from one place to the laboratory and test it and there is also potential damage during transportation apart from that potential during cutting itself.

On the left side you see a tested wallette that it can be done, but it is quite a cumbersome exercise. Of course, it also depends on how many samples you can take, you cannot take unlimited number of samples, but if you have a certain wall in a masonry structure which is going to be dismantled anyway then that is a good location to take a number of samples from. So, you can extract some samples.

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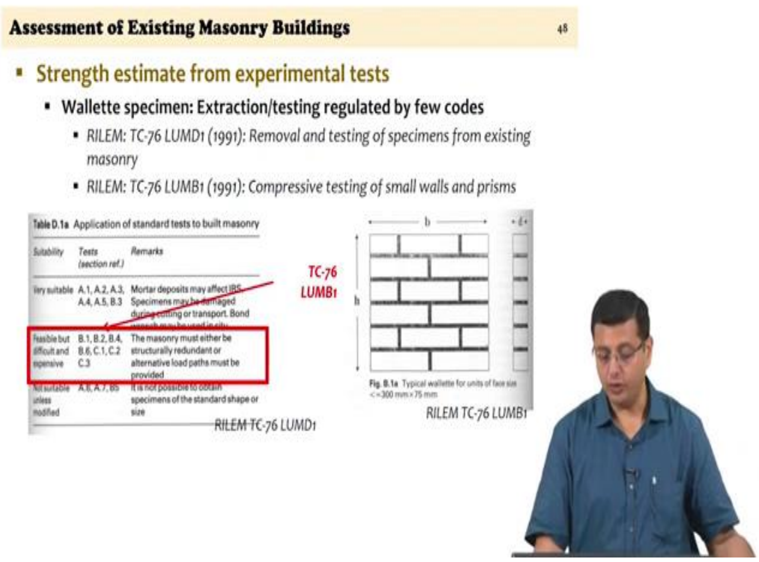

Are they codes as I said that regulate the extraction of samples yes, there are RILEM standards. RILEM is a network of European laboratories and they have examined what should be done if you are going to remove masonry from existing structures for testing purposes and how should you go about compression testing of such prisms. And interestingly, the code actually also underlines that this is a feasible, but difficult and expensive approach which comes back to the first point that I made, it depends on the resources that you have at hand. Time and financial resources, if they are limited you might not want to go for such approach, but if the resources are available this is something that can be done.

So, the code actually tells you what should be the minimum height, minimum width and minimum cross section of such a prism and then you can take it to a laboratory and test it.

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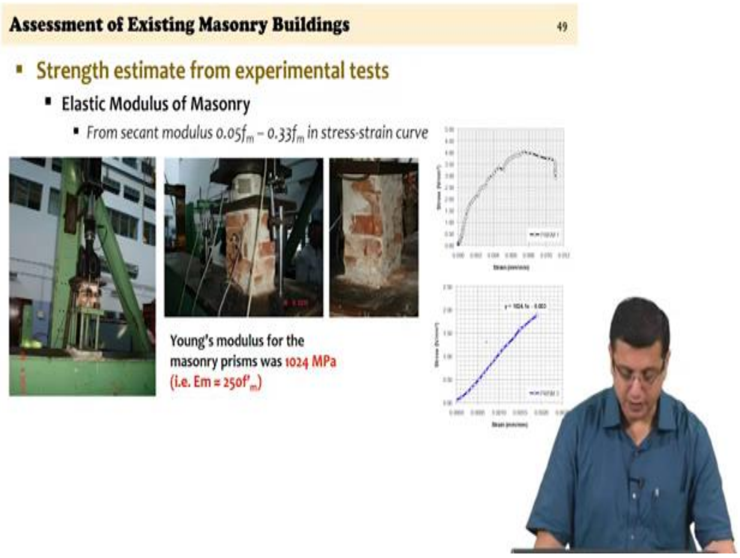

The other thing that can be done is if you were to take a prism to a laboratory; if you were to take a wallette to a laboratory you can get the compressive strength, but in the process with enough instrumentation you can also get the modulus of elasticity and poisson’s ratio from the stress strain curves. So, it is possible that if you take such a wallette to a laboratory, in your compression test you can also get an estimate of what the modulus of elasticity is and with adequate instrumentation even the poisson’s ratio of the material which are parameters that you can directly use in your calculations for strength estimates for the safety assessment itself.

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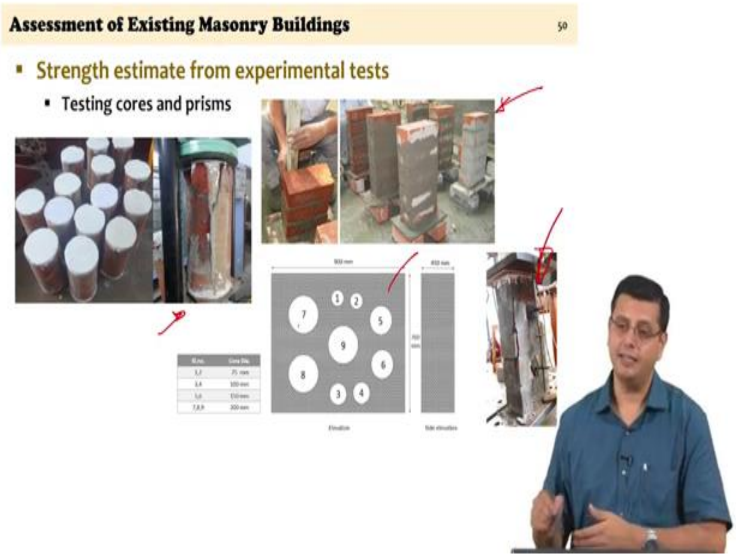

And coming back to the question of course, in some work that was conducted experimental work that was conducted within our master's thesis here at IIT Madras, we looked at how do prisms and cores correlate, are we going completely wrong if we adopt cores and should that not be done when you cannot extract wallettes right it is easier to extract cores whatever said and done. So, we looked at construction of walls from which cores were extracted and then compared it to prism strengths, right.

So, you can see how these how a wall has been constructed and from the wall several cores have been extracted of different diameters, those are the cores and they are being tested in a compression machine as a cylinder and then a number of prisms are also constructed. These prisms are constructed with the same units and the same mortar as the wall it has been constructed and then these prisms are tested in a compression machine as well.

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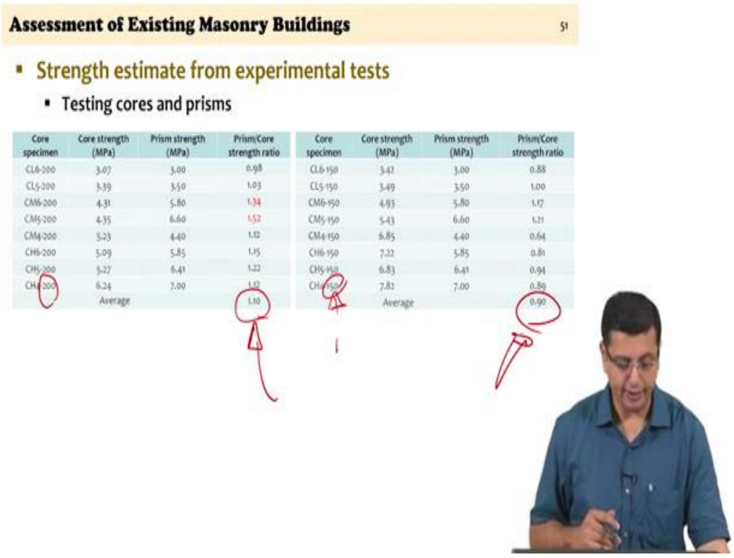

Very interesting results from this test indicated that if you are actually looking at specimens which have a diameter of 200 mm at least right, if you are extracting a small core 75 mm, 100 mm, 150 mm they could be a problem, but if you are extracting 200 mm; minimum 200 mm core diameter two hundred mm; then the prism to core strength ratio is higher than 1, that the core is always going to give you a strength marginally lower than what this prism will give you despite the direction being different in the prism versus the core.

If you look at anything lower 150 or smaller sizes this ratio goes to less than 1; which means, practically speaking if you are looking at a significantly large diameter core like 200 mm or higher. You can use this to establish the compressive strength of masonry and you will err on the conservative side; whereas, if you go for smaller diameter cores you are making a mistake on the non-conservative side. So, if you are using cores do not use anything less than 200 mm, use cores that are large, at least 200 mm or larger otherwise go for extraction of a prism itself. I will stop here and continue with the other tests that we were talking about in the next class.