Design of Masonry Structures

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Module - 05
Lecture - 37
Special Topics – Masonry Infill in RC Frames

Good morning, we are in the last of the modules of this course. These are special topics that we will examine within this, the last module, the last set of lectures. And the first one in the Special Topics is an examination of Masonry Infill Panels and these are typically within reinforced concrete framed structures. So, since a vast quantity of masonry is today being used as infill panels in reinforced concrete constructions, framed constructions, it is useful to understand the behaviour of the masonry infill, particularly in relation to the frame itself. And the interest again is not necessarily from a gravity design point of view, but from earthquake effects on reinforced concrete frames, and the interactions that the masonry panel will have with reinforced concrete frames.

So, today we will look at the problem of infill interaction with the reinforced concrete frame and whether we should be considering the modelling of the panel along with the reinforced concrete frame. And, if we were not to be considering this interaction what could be the implications of that sort of a modelling assumption. And again, what are possible ways of damage limitation in infill, masonry infill panels.

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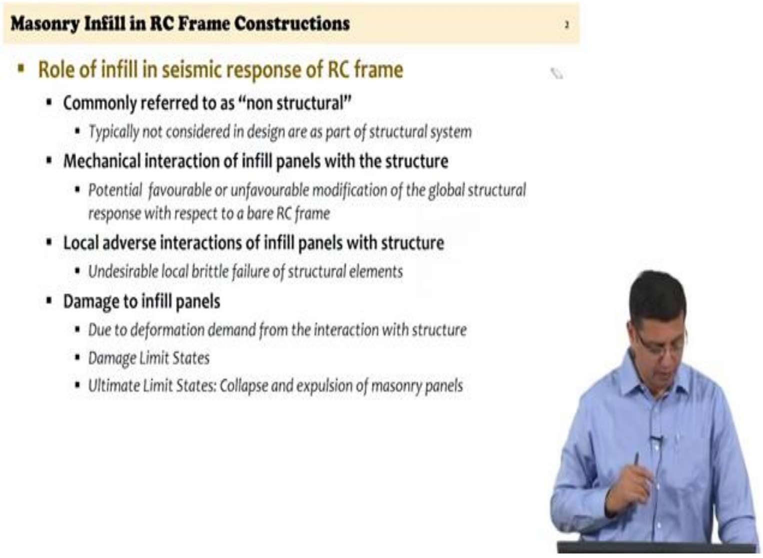

So, the focus as I said is primarily from the earthquake response of reinforced concrete frames. The role of the infill is going to examined as far as the earthquake response of a reinforced concrete frame is concerned. But the standard practice is to consider this as a non-structural element, and standard practice has been to considered this as a non-structural element.

And use the role played by the infill only in terms of the mass modelling. That is the mass of the infill panel is considered in the calculations of the seismic weight. And in the model, this might be considered as a line load acting on the beams but very rarely was this considered to be a structural part of the reinforced concrete frame.

However, the earthquake does not distinguish between a structural component and non-structural component. There is always an effect due to the earthquake and every element in a structure. And these tend to start interacting with the resisting, lateral load resisting element which is the frame and that is where the problem arises.

So, in standard design, this is not considered to be a part of the structural system, which is fair because we do not expect the infill panel to be a part of the load resisting system, the lateral load resisting system. So, from that perspective not considering this as a structural element within the structural design is meaningful; however, there are issues that come because of the possible interaction that is what we are really interested in. So, there is a mechanical interaction of the infill panels with the structure itself.

Now, you can have different scenarios, there could be a favorable outcome of this interaction. But there could also be an unfavorable outcome of the interaction, which means that at the global structural response to earthquakes, you could have a role that this infill is playing to make the seismic behavior desirable or undesirable. And, this you can compare with a bare reinforced concrete frame and understand if the effect is going to be a favorable effect or an unfavorable effect.

So, it is important to understand that there can be a global interaction; an effect that is occurring at the global level by the interaction of the infill panel with the structure. And this interaction could lead to a favorable condition or could lead to an unfavorable condition, but that again depends on a set of parameters which we will also examine.

You can have because of the interaction of the infill panel with the frame, with the reinforced concrete frame; you can have local effects as well. Local adverse effects of the interaction which actually can cause not only localized damage in the panel, but also can cause localized damage in this frame, which is the lateral load resisting element. So, that interaction causing local effects in the panel can have a repercussion on brittle failure mechanisms in the lateral load resisting elements of the reinforced concrete frame itself.

So, infill panels can get damaged right, infill panels can get damaged so, the mechanism of damage of the infill panel needs to be understood. And this damage is occurring because of the interaction of the frame with the infill panel and particularly because the deformations in the infill panel and the deformations in the frame are not similar. When the deformations are dissimilar, at a certain point the infill panel will start interacting with the frame.

And that is where the deformation is really the key to understand when interaction begins and will you have a desirable interaction or will you have an undesirable effect of the interaction. Therefore, it is also since we are looking at deformation; different stages of deformation would mean different levels of damage can be identified. So, damaged limit states have to be identified.

So, if you look at the ultimate limit state of the damage in a masonry panel. The masonry panel would have failed given a certain mechanism; can collapse and get expelled from the frame and this can be a further problem which is a falling hazard. So, at ultimate if the panel is completely failed and is no longer confined within the frame, you have an additional problem of expulsion of the panel which can be a potential falling hazard.

So, the damage to infill panels needs to be understood within the context of deformation demand which will have different effects in the panel, and in the reinforced concrete frame damage limit states have to be identified. And in the ultimate situation failure of the panel and collapse of the panel, expulsion from the frame is a potential falling hazard which can cause a life safety situation.

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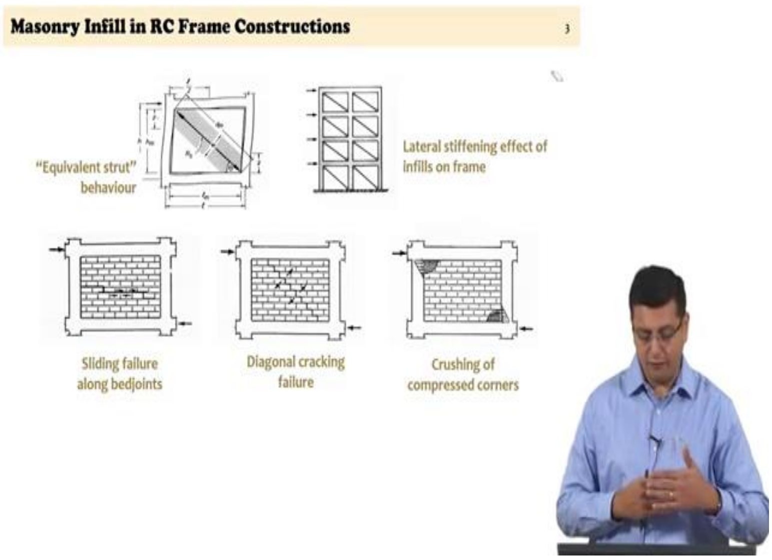

So, the general way in which the panel is expected to behave, when there is a lateral deformation of the frame is by the consideration of an equivalent strut behavior. So, let us assume a reinforced concrete frame made out of the column and the beams within one panel. Expected to deform due to the effects of the lateral force, the infill panel, masonry infill panel which is stiffer because of the in-plane effect that you are looking at, will have lower deformations compared to the reinforced concrete frame, you can consider the bare frame.

These deformations; because these deformations are different, you will have a increase in the compression that will occur across a compression strut that can form. And this is the resisting mechanism once the interaction between the frame and the panel starts getting activated. So, it is possible to examine the interaction between the frame and the panel in the form of an equivalent compression strut that starts forming and starts creating an additional resisting mechanism within the reinforced concrete moment resisting frame.

Now, you might ask what about the other diagonal? The other diagonal when there is a lateral deformation in the reinforced concrete frame is in tension; however, you are looking at an unreinforced masonry panel. And therefore, tensile resistance is far lower than the compression resistance of the masonry panel. And hence the interaction and the effect that comes into the lateral resistance of the frame is more meaningful when considered in terms of the compression strut.

So, what basically happens is, if you where to look at every panel with an equivalent strut it has a stiffening effect on the bare frame. So, if you were to look at your reinforced concrete moment resisting frame as a bare frame, that bare frame is now going to be stiffened due to the interaction of the masonry panels sitting within these frames and the frame itself. So, there is a lateral stiffening effect that is definitely occurring.

What about the panel itself? The panel itself as I said can have different damage limit states, we have seen how a masonry panel, an unreinforced masonry panel, when subjected to lateral forces can have different failure mechanisms; depending on the aspect ratios, depending on the overall geometry and aspect ratios and the different material strengths be it the compressive strength of masonry of the joint shear strength or the tensile strength of masonry itself.

So, similarly different failure mechanisms can be expected in the infill panel which is really an in-plane shear wall; however, sitting within a frame. So, you can expect sliding failure along the bed joints, you can expect diagonal cracking failure as we have seen diagonal tension failure in masonry shear wall. Or you could even have a flexure controlled mechanism, where you have the corners where the compression strut is fully formed; the corners of the compression strut can actually crush; fail in masonry compression and that could be another mechanism.

However, this does not happen independently, this happens within the confinement of the frame. And therefore, there is an immediate effect of the failure mechanism or the different deformation limit states on the frame itself; so it is these two together that we have to actually examine.

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So, if you look at typical failure mechanisms, you have a picture here; you can see that in a multistoried reinforced concrete frame. The infill panel has actually reached its ultimate; post ultimate with continued shaking you actually have a falling hazard which is another important problem that occurs due to the interaction itself. Here again, you can see that an infill is damaged, but then the size of the infill that is damaged is actually going to be affected by the size of openings as well.

So, you might have infill panels which are punctured with openings. So, one has to look at what happens when you have a blank panel, blank masonry panel or a masonry panel which is then provided with these openings. So, immediately you would understand that the equivalent strut that can form in a blank panel can be altered with the presence of an opening. However, depending on the geometry of the panel, a partial strut can still form given the position and the size of the opening itself, ok.

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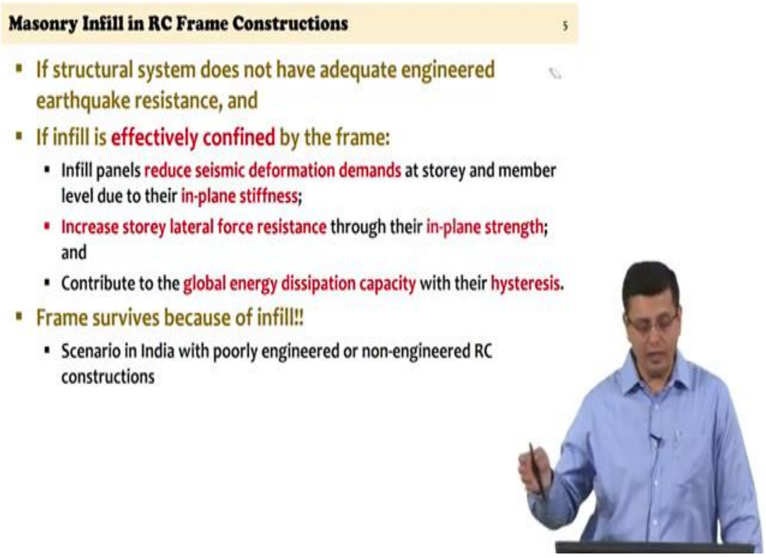

If the lateral load resisting system; in this case, the moment resisting frame, reinforced concrete frame does not have adequate engineered resistance, right. We are talking about earthquake resistance, so this is not designed to resist lateral forces. So, it is a gravity frame and in many cases reinforced concrete frames even in seismic areas are defined as gravity frames because of non-adherence to the code or because many of these structures were constructed before the code actually had specific seismic design guidelines.

So, let us assume a structure does not have the adequate engineered earthquake resistance, but if the infill panel is well confined within the frame, ok, then you could actually have a beneficial effect coming from the infill and the frame interaction. So, the infill panels as I said infill panel is basically an in-plane shear wall considered in the in-plane direction, this has significant stiffness in comparison to the bare frame. And therefore, the infill panel can actually reduce the seismic deformations, the lateral deformation demands at the story and member because of the large in-plane stiffness.

So, it has a lateral stiffening effect to begin with. It can actually also increase the lateral load resistance, lateral force resistance because, the panel is a masonry panel it is a shear wall. And, it can actually because of its in plane strength enhance the in-plane resistance of the frame itself in the direction that you are considering in the direction which is with the panel being in the in-plane loading condition.

So, there is an effect in lateral stiffening, but there is also beneficial effect in terms of additional in-plane strength available to the frame. But, these have not been considered when the structure is being designed considering only the gravity loads. So, it is a gravity designed frame; these effects have not been considered and if the infill is well confined then you can actually have a beneficial effect.

And overall with minimum damage occurring in the infill panel, the panel actually contributes to energy dissipation and the overall the global energy dissipation of the reinforced concrete frame with the infill panel is now acting beneficially for the overall structure under the earthquake action. But the problem comes, when you have good quality infill panels, panels which are constructed well strong in comparison to the lateral strength of the frame itself.

On the other hand, you might have poorly constructed infill panels with poor quality bricks or poor quality material; it could be fly ash bricks or any other type of unit. Now, if the strength of the panel is significantly low and workmanship is poor then, the panel starts getting damaged and participates in global energy dissipation and in a way will start protecting the frame.

However, if you have a frame which is not designed adequately for earthquake effect and if you have a panel which is super strong, a panel which is built using strong units then, damage will be limited in the panel and they will be an effect because of the interaction on the frame and the inadequately designed frame can fail.

So, this is where I was talking about the interaction can lead to a favorable effect or an unfavorable effect. What typically happens in western contexts, where frame is not designed for earthquakes, but because of good quality units available and workmanship being good. You will have a strong panel interacting with the frame leading to failure of the frame. So, that is an unfavorable effect.

In the Indian context; often we have seen that since the quality of bricks is typically poor and workmanship is also poor in areas in the rural areas, in the semi urban areas, where construction procedures are not thorough. The frame is very often protected by the damage occurring in the infill panels and there is a dissipation that comes from the panel which then in a way protects the overall frame. So, that is the Indian context it has been well documented in several of the recent earthquakes in the last few decades that the bare frame. If the bare frame did not have, if the frame did not have infills, infill panels it could have failed.

But, the presence of the infill actually limits the damage in the structure to non-structural damage, which is damaged in the infills and the frame has survived. And we are talking of frames which are not designed seismically. So, this is a scenario, which is particularly not only in India, but in several of the developing countries this scenario is observed; Turkey for example, with poorly engineered or non-engineered reinforced concrete constructions.

So, the favorable and unfavorable is conditions come from in non-designed frames, what is the quality of the units and what is the quality of the workmanship itself, ok.

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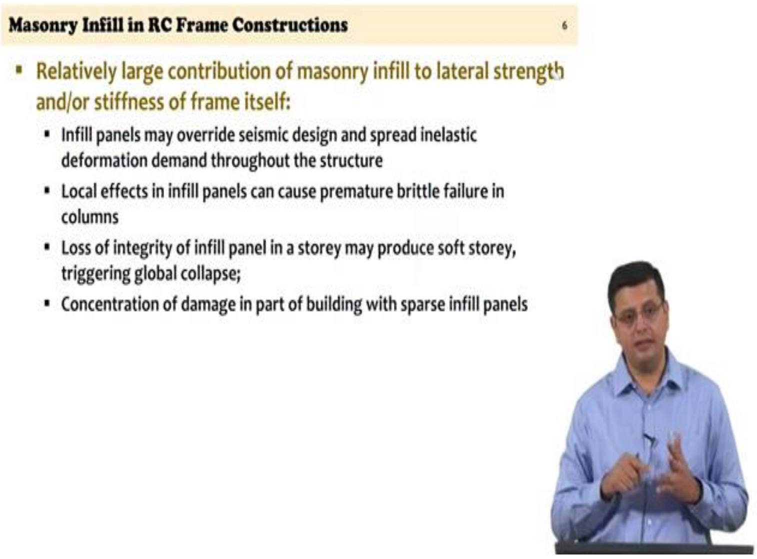

So, when there is a relatively large contribution of the masonry infill to the lateral strength or stiffness of the frame itself; what could happen is that, the infill panel would override the seismic design; the reinforced concrete moment resisting frame could be designed seismically. But, if the interaction is not considered, if the additional effect of interaction is not considered then, these strong panels would then lead to a condition where the demand on the reinforced concrete frame is higher than what was expected as a bare frame.

And you will have inelastic deformation that will start spreading through the structure, throughout the structure which was not expected because your modeling and analysis was based on a bare frame. So, even if seismic design were to be considered in a moment resisting frame, if the interaction is not considered. And if you have strong infill panels, the problem is the demand will increase, because the stiffnesses are changing. And it can cause inelasticity to spread in the moment resisting frame.

So, these local effects can occur, we saw the possible failure mechanisms in the infill panels it could be sliding, it could be diagonal cracking, it could be corner crushing. And those localized mechanisms, if the panel were to be taken to that state of failure, it could cause additional shear forces in the frame which can cause brittle failure mechanisms in the columns which is then undesirable in the overall, in the global behavior itself.

And again, if you have panels which are let us say failing once they reach the ultimate are completely lost; then the distribution of stiffness in the structure suddenly changes. You might have one story, which is then suddenly becoming a soft story. Whereas, the other stories continue to have the infill panels you can have a sudden soft story failure getting triggered in the seismically designed moment resisting frame, so that is again a serious problem.

Again, if you are designing the moment resisting frame as a bare frame and have not considered a non-uniform distribution of the infill panels in different parts of the building, that has an effect in terms of additional torsional forces coming in. And you can have concentration of damage in the flexible site of the structure, where infill panels are sparse. So, this is a problem because of non-consideration of interaction effects in seismically design moment resisting frames considered as bare frames.

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Let us look at the global effects of the frame infill interaction because of an irregular distribution of infill panels in plan. You might have regular distribution that could be one case, but often you can even have an irregular distribution of infill panels in plan.

So, what is really happening is, you get additional torsional forces coming in because there can be a shift in the center of rigidity to the center of stiffness that we talked about and then the deformation demand starts becoming non-uniform. The stiffer side getting smaller deformation, the more flexible side getting larger deformations and damage concentration happening in regions where infill panels are not adequately provided.

What about in height? You could have a similar situation that let us say you have the ground story which is meant for parking and it is a bare frame literally in the ground story. Whereas, as you go to the upper stories of residential buildings, commercial complexes, you have a large number of infill panels. Now, the stiffness of the upper stories is very different from the stiffness of the ground story and unless this is considered in the lateral force design.

Then you have an irregular distribution of stiffness is in elevation and can trigger soft story mechanisms or the failure mechanisms that are typically seen with the open ground story as you can see in these pictures. You can see that the upper stories have almost survive without any non-linearity, any inelasticity. Simply because there is a certain uniformity and higher stiffness in those stories whereas, the weakness is in the region where it is a bare frame action and not the interaction that is available because of the presence of the panel itself.

For all you know presence of the panel in the basement or in the ground story, would have actually saved the structure. And this is what I was mentioning in the earlier slide that it has been documented in Indian earthquakes that infill frames can actually; say infill panels can actually save the structure under earthquake actions, ok.

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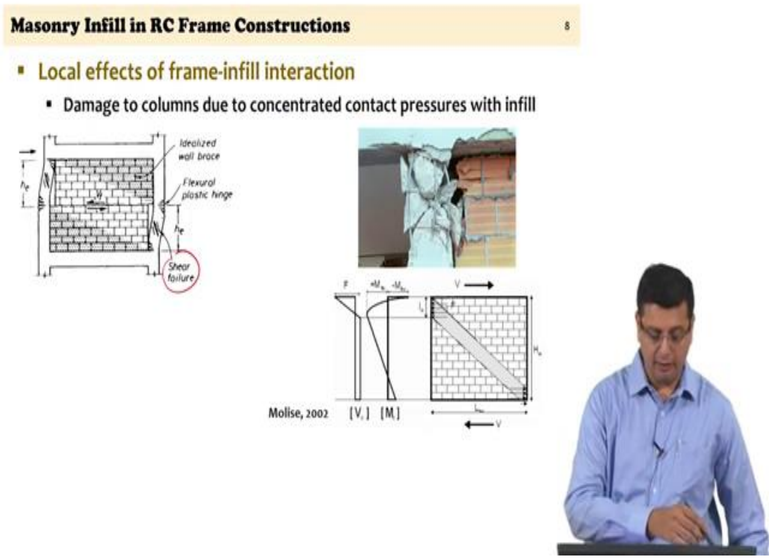

What are the local effects of frame infill interaction and the how does this then have a role to play on the additional demands coming onto the framing elements. Now, if there is a failure in the panel, let us consider a first failure mechanism where the panel is failing due to shear sliding, right. We consider shear sliding typically to occur in a masonry wall, in a masonry shear wall unreinforced masonry shear wall at the ground at the lower most courses, right. It can happen at the lowest course or one of the lower courses.

However, here because of the deformation of the panel and the deformation of the frame and the contact pressure typically you should expect the shear sliding to occur that mid height. But, then when shear sliding occurs at mid height, then you have the shear force and the shear deformation of the panel, causing at the mid height of the column itself additional forces which can cause the formation of a plastic hinge, which is because of the sudden increase in deformation demand at that zone. Plastic hinge can form and the the column height is now one half and the shear demand on one half height of a column suddenly increases and unless this interaction has been considered, you can have shear failure occurring in the short column due to the way the panel fails.

So, this mechanism is occurring because of the failure mode in the panel, failure mode in the panel is creating the effect of shortening the column. And in a shortened column the shear demand is augmented and unless it is accounting for the interaction, you can have premature shear failure in the column. So, this sort of a failure mechanism, what you see here is due to the contact pressure.

The figure on the left, the contact pressure is established and increased deformation to the frame is occurring after sliding failure of the panel itself. The figure on the left is when an effective strut is formed, you have contact of the infill panel with the reinforced concrete column. Here the contact is occurring close to the beam column joint and this additional shear force that comes in at this zone.

If the reinforced concrete column is not adequately designed to have necessary links necessary ties in that zone adequate number of ties in that zone can cause shear failure in the reinforced concrete column itself. So, you can see that it is; this transfer of shear forces due to contact pressures that has increased the shear demand on the panel it’s the same in both the cases; even in the case of the where the panel is failing by shear sliding.

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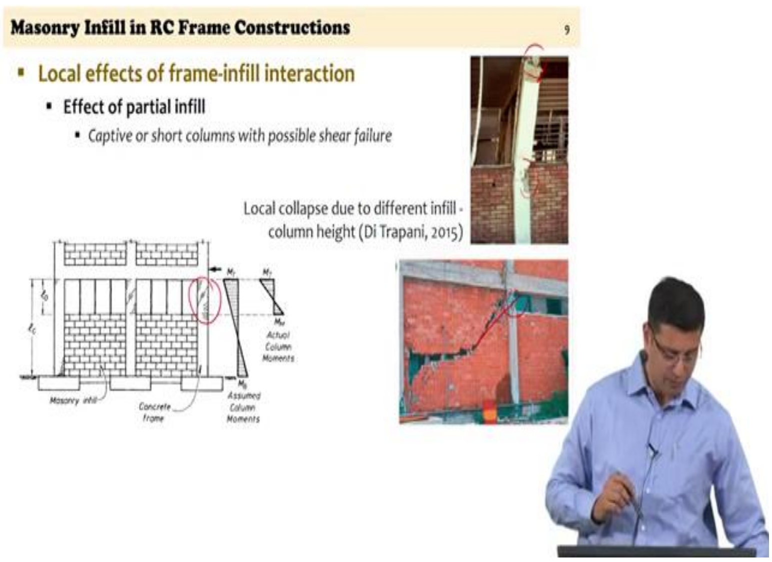

In several situations to provide ventilators or to provide windows, you might have a partial infill. Again, the partial infill has the, has also the effect of creating a short column or a captive column. In the previous case, the failure of the infill panel created the short column effect or the deformation could cause, because of an effective strut, contact pressures at the corners of the column and cause failure in the reinforced concrete column in the corners due to shear failure.

In this case the panel itself, to begin with is of a geometry, because of the openings creating a short column effect in the reinforced concrete frame. So, if you were to consider bare columns, bare frame versus a frame which has a partial infill there are additional moments coming at these critical zones. Like the sliding shear failure that you saw earlier, you can see that additional shear forces in that reduced height column, where the opening is going to cause shear failure unless you have accounted for this and provided ties in that region.

So, you can see that presence of different height infills across the reinforced concrete frame that is being considered; you can see the case one below we are sort of a sliding failure has initiated, whereas in the other one you already have a partial height infill. So, these because of the interaction create additional shear forces in the reinforced concrete column. You can see the formation of the plastic hinge here in the reinforced concrete column itself; you can see the shear failure that is caused because of the interaction with the infill at the corner.

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Out of plane expulsion of infill panels, let us say the predominant direction of shaking is not aligned with the in-plane axis, along the longitudinal axis of the infill panels; if the shaking is in the other direction, then you can get expulsion of the infill panel. And now if the infill panel is not well confined, you can get expulsion. You can also get expulsion due to the random nature of shaking; infill panel gets damaged and then the damaged infill panel which is no longer confined can also fail in out of plane direction.

In this particular case, you can see how infill panels have been completely pushed out that they have not been well confined within the frame could be one of the reasons. In multistoried structures, you can imagine falling panel from a three or four story, five story structure is going to be a serious life safety hazard.

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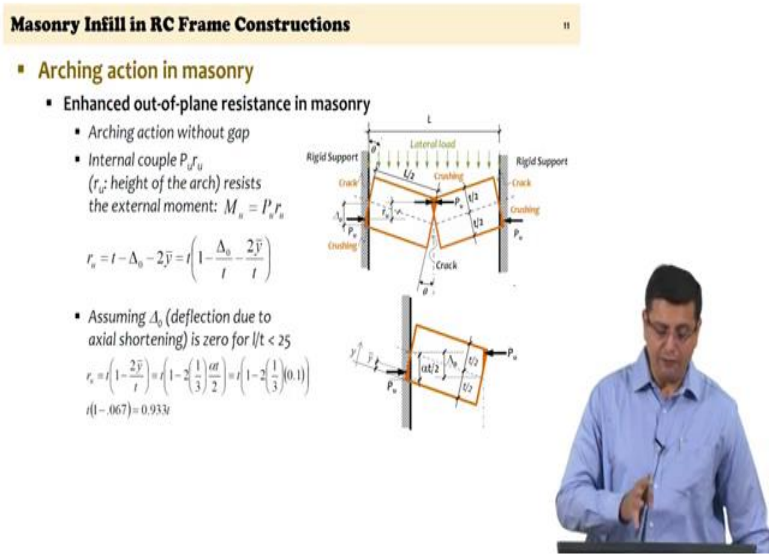

In this context we have actually seen, how arching action, we have arching action in masonry earlier and I did mention that, particularly with respect to infill frames, infill panels in reinforced concrete frames, this is a beneficial mechanism and needs to be considered. So, arching action you are talking of the infill panel trying to deform and fall outwards deform and fail in the out of plane direction. But, if arching action is available then the resistance of the infill panel to the out of plane action is significant.

So, we are earlier lectures we were talking of non-moving supports, here the reinforced concrete frame can be considered to be the rigid support with respect to the infill panel. And you have also seen how considering arching action, significantly increases the out of plane capacity of a wall as against the conventional bending analysis in the out of plane direction.

So, just to recollect; assuming that there is no gap; that the workmanship or and the design is such that there is no gap between the infill panel and the wall, which is the infill panel in the out of plane direction. Then it is possible to establish what the resistance is the out of plane resistance being M_u which is which can be estimated based on estimate of the clamping force and the rise of the arch that can form. So, P_u r_u will give you the out of plane resistance.

And we have made some simple geometrical calculations to arrive at the estimate of this arch in our earlier slides. So, I am just just summarizing it and typically when the l/t ratio the length to thickness ratio, here we are considering the horizontal bending. If the slenderness ratio is less than 25 and as long as we are assuming small deflections these formulations are acceptable.

So, the rise of the arch we have estimated to be about 93 percent of the thickness of the wall itself and that significantly increases the out of plane capacity of the infill panel with respect to non-moving supports. If the gap is not present, we are really considering rigid arching mechanisms.

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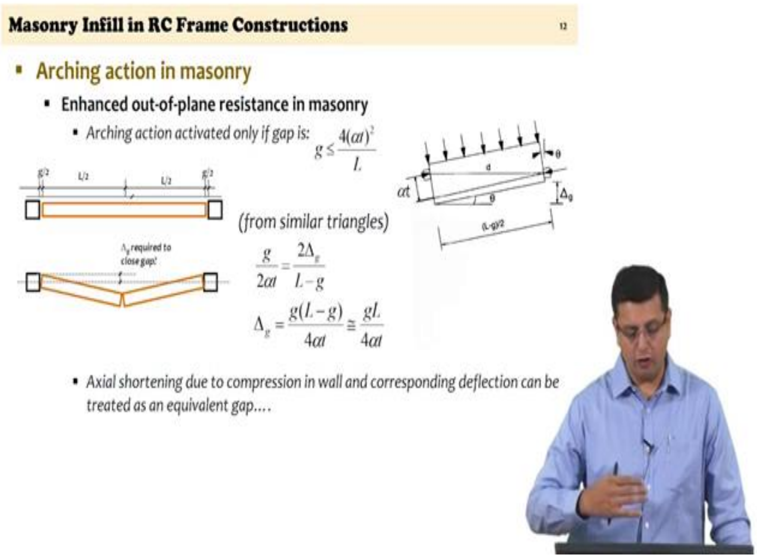

However, if you actually have a gap, if you have a gap then we have seen from geometry that if you want this arching action to be available. There is a limitation geometrical limitation on what the gap should be; we have seen that as well. And then we can estimate what this Δ_g should be to close the gap. Here we are assuming that g/2 and g/2 is the size of the gap on the two ends of the panel itself.

So, primarily by looking at the geometry, where αt is a percentage of the total thickness, where the clamping force is actually acting and this αt is to consider some amount of softening that can occur in the masonry due to the additional compression. If you were to consider the similar triangles in this case, we can actually write down an estimate of what; how much of deformation of the panel is essential Δ_g in this case such that, the gap is closed and arching action can actually be made use of.

So, an estimate of Δ_g can be made as gL/4αt. αt here we have been considering about 90 percent of the total thickness itself.

Now, the other thing that can happen is they can be axial shortening, if there is significant deformation, they can be axial shortening due to compression. And then you can look at the deflection itself being treated as a gap that is forming right, that is what will happen. Let us say to begin with there was no gap, but then with the wall deforming and if the out of plane deflections are significant, then there will be axial shortening which means a gap can form and within the limits of what that formation of the gap is going to reduce the effectiveness of the out of plane resistance itself. And when the gap exceeds the allowed geometrical limit, you will have no longer resistance of the infill panel in the out of plane direction and that is when you get expulsion of the masonry panel itself.

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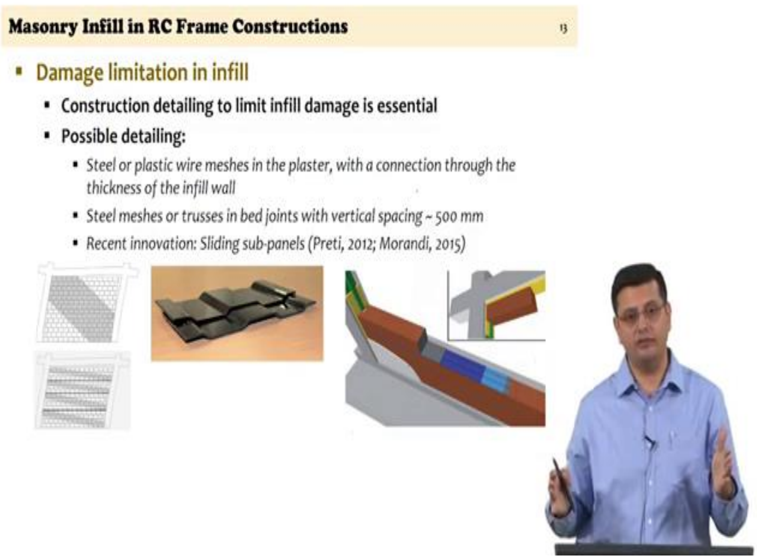

Recent studies and this is something that has caught the attention of several researchers worldwide which is, it is important to limit the damage in the infill panel. Particularly, because of the hazard of a panel getting expelled from a masonry, from a reinforced concrete frame. So, if the panel can be retained within the reinforced concrete frame then certain limit states can be achieved particularly, the life safety limit state against falling hazards.

So, recent works have looked at bringing in construction detailing to limit infill damage. Now, I would like to mention that constructions in India, in reinforced concrete frames, if you look at CPWD manuals, this is a detail which has been around for 50-60 years now. Infill panels are constructed with a small RC band; a small RC band at every one meter height ok. And these RC bands are sitting within the infill panel.

Now this is meant to limit the out of plane deformation of the infill panels. Actually, prevents the expulsion of the infill panel in seismic areas. So, there has been, there are detailing requirements which actually take into account damage limitation and infill panels. There are some recent procedures or recent detailing requirements which try to limit the damage in the out of plane direction in the infill panel. So, wire mesh is placed in the plaster and this can be a steel or a plastic wire mesh with lot of these geogrids available today; it is possible to have rather thin joint.

So, steel or plastic wire mesh is placed in the plaster and you connect it across the entire thickness of the wall panel. Basically, what is going to do is, the wall is now, the panel is now divided into smaller sub panels within which the strut will develop. So, each of those have to fail for further, I mean to reach the ultimate limit state and further expulsion to occur. So, by splitting these into sub panels, the capacity of the infill also can be enhanced.

So, other examples are trusses being placed in the bed joint. These are all in the infill panel; these are all non-structural elements. There were also been new innovative designs where the panel starts working as sliding sub panels, you have some energy dissipation that is available in the joints.

So, these help in energy dissipation, limit the damage occurring to the infill panel. And hence you have enhanced behavior this is one recent work where you actually have this sliding joint capable of dissipating some energy. But, the whole idea is to work on sub panels you are not having the large masonry panel which transfer significant forces to the contact pressures with the reinforced concrete frame. By breaking it down to sub panels the contact points then transmit smaller pressures to the reinforced concrete frame and thereby you protect the reinforced concrete frame as well, ok.

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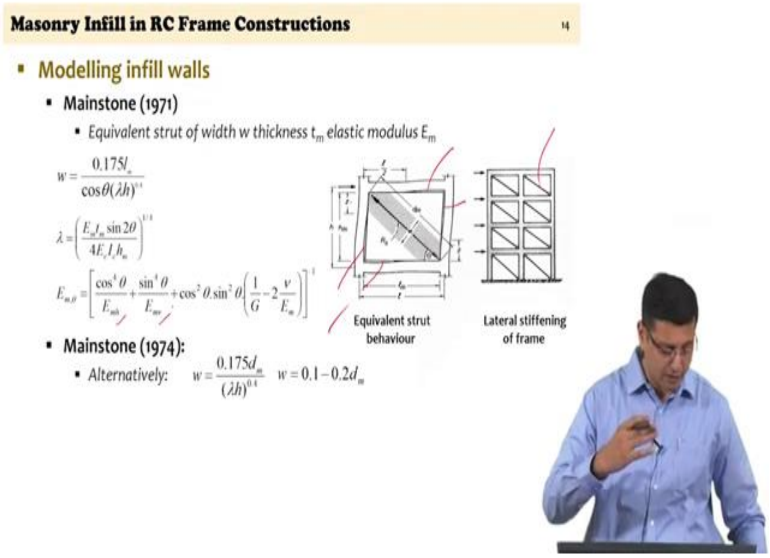

The final thing that I would like to look at is, it is required that these infill walls, infill panels are considered in the seismic design. Because, you have seen the possible effect infill panels can have on the lateral load resisting system in the case of a moment resisting frame itself. This is an area which is received adequate research focus, but is a subject which has a significant amount of uncertainties. Because, there are several parameters that govern the behavior of an infill panel and then its interaction with a reinforced concrete frame.

Hence, you have a number of approaches available to model infill panels, and the several studies look at comparing these many of them are empirical, many of them are semi analytical or semi empirical. So, those of you are interested in looking at understanding how infill panels can be modeled. You should be prepared look at a very large body of research in the subject both experimental and analytical.

One of the most cited and the most used with respect to codes, with respect to international codes is a formulation by Mainstone in 1971; however, this formulation has then been modified by several successive works, but also simplified by code formulations. The IS code formulation follows a similar; the IS code, IS 1893 part one 2016 version gives one method by which an equivalent strut can be modeled in the frame modeling. And the calculations which can be adopted to arrive at the width of the equivalent strut is based on the Mainstone formulation.

So, the equivalent strut, strut that we are talking about is with the deformation of the panel; masonry panel being lesser because it is stiffer than the framing element. You will have partial contact, you will not have full contact of the panel with the frame you can see that there is joint opening; there is joint opening that is occurring here between the panel and the frame. The contact, the effective contact is limited to an equivalent strut is limited to a strut a compression strut that forms, which means the whole panel is not resisting, but it is only an equivalent strut of the panel it is only a partial strut of the panel.

Now, effort has been dedicated to model this interaction between the frame and the masonry panel using this equivalent strut. So, if the size of the equivalent strut particularly the width of the strut can be established, then you can model the moment resisting frame with additional braces, whose cross sectional dimensions come from the equivalent width of the strut and the thickness equal to the thickness of the panel itself, right.

So, this is basically what the approach is, important parameters here are definitely the aspect ratios the wall. What is the, is the panel actually having a minimum slenderness ratio. And then slenderness ratios are between 12 and 20 we are comfortable that it can give significant stiffening effect and the length of the strut the length of the strut is taken as the length of the diagonal itself.

So, d_m is the length of the diagonal that you talking about and that is the effective length of the strut, w is the width of the strut, which is what is established based on mechanics and based on experimental tests and observations from experimental tests. So, Mainstone's work again is to be able to arrive at the width of this equivalence strut. And then you can use this width of the equivalent strut to model and additional brace, which has a cross-sectional dimension w/t which is the thickness of the masonry panel itself.

So, if the wall thickness, which is the thickness of the masonry panel is t_m and elastic modulus of the masonry can be estimated as E_m; it could be 550 f'_m if you do not have the actual modulus of elasticity of the masonry. Then considering the angle of the strut with respect to the frame θ, the width of the panel can be written down semi-empirically. Where λh is actually the lateral stiffness of the panel, which is the critical element; the lateral stiffness of the panel which is a contribution to the interaction itself.

So, λh is then estimated; lambda h is then it estimated based on the relative stiffness's E_m to E_c, where E_c is the modulus of elasticity of concrete E_m is the modulus of elasticity of the masonry. And this is arrived at based on observations of the mechanical behavior and also experimental results. In case they estimate of the modulus of elasticity, there are as I said several versions of these formulations; some of them become very rigorous, some of them can actually give you an estimate of the modulus of elasticity, effective models of elasticity that must be considered depending on the geometry of the panel.

And the modulus of elasticity of the panel considered in an angle with respect to theta at theta itself can be estimated from the modulus of elasticity of masonry in the horizontal and vertical direction. So, these are additional steps that are available to make the model more rigorous and match experimental results. The modulus of elasticity of masonry in two directions can be different. And if you were to look at the behavior of the strut, then you are interested in compression along the strut and the modulus elasticity needs to be estimated based on what the angle θ is.

So, there are formulations there are specific details of these formulations. The simplified version of this is what the IS code actually has. When you do not have an estimate of the models of elasticity along in the vertical direction and the horizontal direction of masonry depending on the bed joint orientation, then simplified versions are available; where simple simpler that available where you can actually use E_m as $550f'_m$.

Or in this case it is also been seen that the width of this strut is typically between 10 to 20 percent of the length of the strut within limits of the aspect ratio of the wall itself. So, most importantly it is about λh; λh is the effective lateral stiffness of the panel arrived at considering the masonry modulus of elasticity, its relation to the concrete modulus of elasticity and the angle that the strut makes with the frame itself.

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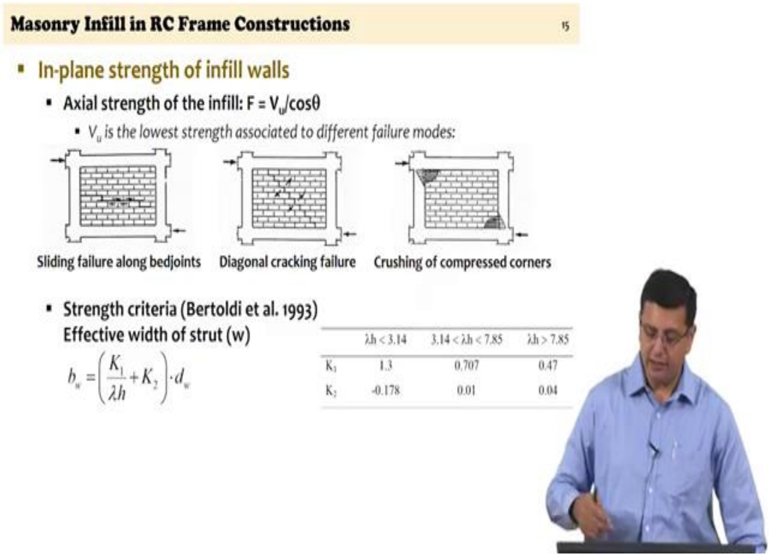

	λh < 3.14	3.14 < λh < 7.85	λh > 7.85
K1	1.3	0.707	0.47
K2	-0.178	0.01	0.04

There have been other studies that looked at; they have looked at the earlier study the earlier expression was to arrive at a width of the equivalent strut. So, that you then go to your model and you can actually model the interaction using braces in the design itself in the model of the reinforced concrete moment resisting frame itself.

So, therefore, that was more from a stiffness point of view. In terms of strength, the strength of the infill panels; the axial strength of the infill panel is estimated based, you are looking at the equivalent strut. And you want to know, what is the force at which this equivalent strut is going to fail? So, you are interested in looking at the failure in the infill panel in shear and then correspondingly estimate based on the angle theta what the failure force of the panel itself is. So, the in-plane strength of the infill panel can be estimated.

Now, V_u is the ultimate shear force in the panel which is then associated to the failure mechanism. It could be sliding shear failure, it could be diagonal cracking failure or it could be a flexural failure mechanism with the ends failing in masonry compression. So, again there are different formulations available to be able to arrive at the in-plane strength of the infill panel. As I said this depends on the aspect ratio.

Aspect ratio of the wall panel and different mechanisms can form depending on the aspect ratio, which is true even for unconfined load bearing masonry shear wall itself. So, one of the works that you could go back to estimate strength of the infill panel is by

Bertoldi, where the factors that you see K_1 and K_2 have been arrived at calibrated from experimental results of different panel sizes.

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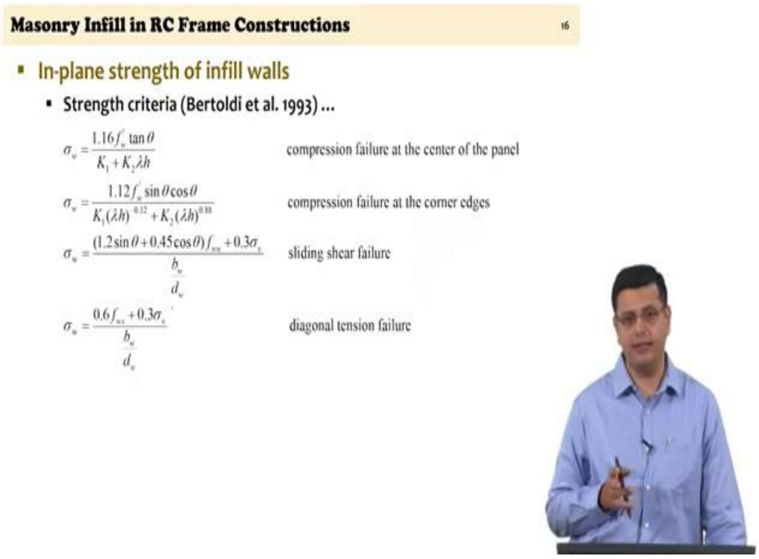

So, the strength of the infill wall panel in this strength criterion, that you looking at; different strengths of the infill panel are worked out based on the type of failure mechanism that you see. So, depending on whether the panel has failed by compression failure, at the center of the panel you can have the strut failing in compression at the center. Or you can have the strut failing due to compression because of contact at the corners, or you could have sliding shear failure or you could have a diagonal tension failure as you have seen earlier.

So, these formulations are formulations which are based on an understanding of how the panel is failing, but by interactions with the frame itself. So, there are works which can help you arrive at semi empirically estimating in plane strengths. And in plane stiffnesses which can contribute to modeling the interaction of the panel with the frame in your seismic analysis and design of reinforced concrete frames.

So, this is a special topic, I have not gone into details of formulations, but is intended to give you an idea of what considering the interaction or not concerned considering the interaction can lead to and possible ways of looking at strength and stiffness modeling of the panels themselves, when you are designing frames, moment resisting frames for seismic resistance. I'll stop here and take questions if there are any.