Applied Seismology for Engineers

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Week – 12 Lecture - 03

Lecture – 30

Hello everyone. Welcome to lecture 30, which is the last lecture for this particular course, Applied Seismology for Engineers. In the last two lectures, that is, lecture 28 and 29, we have discussed seismic vulnerability as well as seismic risk. In lecture 28, we have seen that based on the earlier understandings, whenever we are getting the value of seismic hazard, that is, the expected level of ground shaking, expected level of earthquake loading during a particular earthquake or during a particular exposure period, which is likely to be experienced by a particular building, the building may undergo severe damages, it may undergo slight damages, and there might be some kind of collapse also in the building. So, in order to forecast what potential level of damage can be experienced by a particular building during likely-to-occur ground motion, taking into consideration the exposure period, which can be maybe 20 years, 30 years, or 40 years, and taking the seismicity as well as the condition of the building in its present situation, one can go ahead with the assessment of seismic vulnerability. Later on, taking into account how much is the loading which is going to come and how much are the characteristics of the building with respect to codal provisions, in terms of irregularities, in terms of plan, and in terms of site conditions, one can determine the relative vulnerability of a particular building. Then, taking this into account and considering the exposure period, we can go ahead with a risk assessment.

In lecture 29, we discussed that primarily two methods are there for seismic vulnerability assessment. One is based on the empirical method, that is, mostly like rapid visual screening, taken into account the codal provisions which are given. In rapid visual screening, we have to find out the type of the building, we have to find out what are the different parameters or characteristics of the building, including codal detailing, site condition, whether it is located on a liquefied site, whether it is located on a non-liquefied site, or site class 1, site class 2. Similarly, if there is any irregularity in terms of plan, if there is any irregularity in terms of elevation, that has to be observed carefully while going around a particular building or while observing a number of buildings in a particular region for which vulnerability assessment is important. Taking the base score, as we have discussed in lecture 29, into account and successfully considering other properties also, which are the score modifiers, one can determine the value of S, that is, the score based on rapid visual screening. Then, corresponding to the value of S, there are the characteristics and classifications given, based on which one can identify what level or grade of damage, with what probability, whether it is moderate probability, high probability, or very high probability of grade 1, grade 2, grade 3, grade 4, or grade 5 kind of damage which is likely to occur in a particular building whenever it is exposed to a certain earthquake loading condition, corresponding to the seismic zone in which the building is located, and corresponding to how the seismic zonation factor is getting modified, based on a given site condition and codal detailings. So, all those things we have discussed in lecture 29.

We have also seen two examples where two buildings were given, and then, taking into consideration where those buildings are located, which particular seismic zones the buildings are located in, and what type of buildings are those, the corresponding value of base scores was obtained. Then, again, observing with respect to the form available from the Ministry of Home Affairs, Government of India, you observe different specifications of the building, in terms of maybe diaphragm, shear walls, lightweight materials, or wooden frames. We can find out specific details and correspondingly the score modifier. Finally, we got the value of the score for both buildings, and depending upon the score, we compared it with respect to grade 1, grade 2, up to grade 5, corresponding to the score, explaining the damage of the building. This method, that is, rapid visual screening (RVS), is primarily used for empirically understanding, based on visual screening of a building. You do not require any specific information as far as the earthquake characteristics are concerned, or as far as the building characteristics are concerned, because you are simply observing the building visually. Based on the observation, if you find specific characteristics of the building that are visualized just by looking at the building from the outside, you report it.

That is why, when we were discussing seismic vulnerability, primarily based on rapid visual screening, it was highlighted that many times vulnerable buildings are highlighted as not vulnerable. Similarly, there are buildings which are found as vulnerable but actually are not vulnerable. In both cases, vulnerable buildings can be found as not vulnerable, and non-vulnerable buildings can be found as vulnerable. One also has to take into account that the person who is actually observing the characteristics, which is given in the forms, is not an expert; it is a person who might be trained for some time so that he or she can go for field observations. There are certain points that have to be considered before going for field observations or before planning for field observations. Then, after going to the field, you can later on come back to the laboratory or your office and note down or look at the database observed during a field investigation corresponding to different buildings.

So, this seismic vulnerability, based on rapid visual screening or based on empirical methods, is going to give you a quick, rough idea about the vulnerability of the building, taking into consideration the importance of the building, the historey of the particular building, the materials used in the particular building construction, and similarly other factors. One can decide, of course, after taking into account the grade of damage which has been found based on the empirical method. One can go ahead and decide whether a detailed investigation is required, where specific properties, whether numerical modeling of a building or some experimental setup which may give you some demand of a particular building or the capacity of a particular building, can be taken into consideration.

That means if you are not dealing with an important building, you can directly go with rapid visual screening. If you are dealing with routine buildings and trying to find out the vulnerability, you can go ahead with rapid visual screening, and then, accordingly, buildings which even appear to be vulnerable or are found vulnerable, the corresponding authority may take a decision whether it is required to undergo retrofitting or strengthening, or if the building can be demolished before a particular earthquake loading actually hits the building. Similar consequences of damage which have already been indicated based on rapid visual screening at a particular site can be implemented. Similarly, if there are important buildings which cannot be demolished or some important structures which, based on rapid visual screening, demand retrofitting or strengthening, we can go ahead with analytical methods. These will exactly give you an idea about how much demand is generated based on earthquake loading conditions. Taking into consideration material characteristics, the position of beams, columns, reinforcement details, and applied load, one can actually go for the design as well as the analysis of a particular building. You can take all the design parameters and model a particular building. Again, when we are going for modeling, primarily these two kinds of loads will come into the picture, which we have also discussed in lecture 29. First is gravity load, which will be there every time whenever we are talking about live load and dead load. In addition, we are also talking about earthquake load. So, if you take into consideration the magnitude of live load and dead load, the magnitude is more or less defined, but whenever it comes to earthquake loading conditions, it's not only the magnitude but also the variation in the magnitude over time. Thirdly, earthquake load is actually reversible in nature. So sometimes you are having shaking in one direction and considering that earthquake loading condition is cyclic in nature, there will be cycles of loading and unloading, or loading in one direction and subsequently loading in the reverse direction, or almost in the opposite direction.

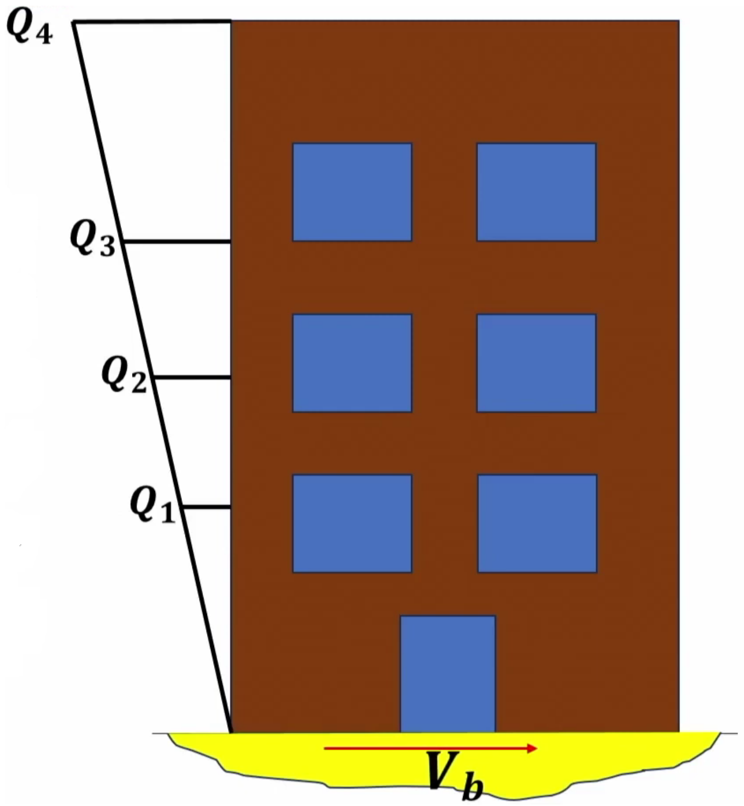
So, taking that into consideration, we can analyze, corresponding to gravity load, how much earthquake load is going to be transferred to a particular building. There also, whenever we are going for analysis, primarily, we can go with static analysis, taking maybe gravity load as well as some form of coefficients determining approximately how much earthquake loading is going to be applied. So, some static analysis or maybe pseudo-static analysis can be performed. In addition, if you are going with dynamic analysis or taking into consideration the formation of plastic hinges or restricting the yielding of the material as the ultimate stage for responding to the external loading condition, we can again restrict it to linear analysis and nonlinear analysis. So, generally, when we go for linear analysis, we are restricting it to the elastic range in which the material is going to offer resistance to the external loading condition. Taken into consideration maybe representative strength characteristics of the medium. On the contrary, if you are going with nonlinear analysis, we will take actually the hysteresis loop, how the material properties, how the material strength properties are degrading or changing as the earthquake loading condition, which is cyclic in nature, is applied to a particular building. So, we can take into account maybe beams, columns, shear walls, and other subsequent members, which are going to offer resistance to earthquake loading conditions. Either we can go with the linear analysis, or we can go with nonlinear analysis, where we will see how the material characteristics, with every cycle of loading, are undergoing degradation or change in its strength characteristics or change in its resistance properties over the period of time for which earthquake loading has been actually applied to the corresponding member. So, there, you can go with the nonlinear analysis and find out what is the actual capacity of a particular building and then compare with respect to the demand, which you can get maybe from codal provisions or from seismic hazard analysis.

So, in today's lecture, we will be discussing again in brief about what is pushover analysis, how linear and nonlinear analysis are generally taken into consideration to again comment on the vulnerability of the building or to get an understanding about the damage characteristics of a particular building. As I mentioned earlier also, it is not only the vulnerability, but at the same time, based on hazard analysis, if you have found out that a particular level of ground shaking is expected to be experienced by a building during its design life, then it is not only the magnitude of ground motion, that is spectral acceleration, spectral velocity, or spectral displacement, but at the same time, one has to also take into consideration what are the ground motion characteristics, which are also varying, keeping in mind that the amplitude of your ground motion parameter is not changing. That means you are having a different magnitude of earthquake happening at different distances; even these two combinations can contribute to almost the same amplitude of ground motion. Similarly, depending upon how far your earthquake source is there with respect to your site, what is the propagation medium characteristics, what is the medium available between bedrock and the surface, again, your motion characteristics—primarily the duration as well as the frequency content—and subsequently, the amplitude also is going to change. So, how these three things, that is amplitude, duration, and frequency content, all these three parameters of a particular ground motion corresponding to which the amplitude has been taken, either referring to seismic zonation maps or based on seismic hazard values.

So, all these can also contribute significantly to the response of the same building. You are applying maybe 0.2g, you are applying maybe 0.25g, 0.3g, 0.36g, so the amplitude remains the same, but when you are going with nonlinear analysis, the characteristics of ground motion will also play an important role. So, we will take into account a lot of such characteristics and try to find out, with a change in these characteristics, how the response, in terms of damage, in terms of capacity, or finally in terms of damage, is changing in a particular building, in a particular infrastructure, keeping in mind that the amplitude of loading is more or less remaining the same.

So, we will start with pushover analysis, which will help us in understanding how much, corresponding to an earthquake loading condition, the maximum displacement in a building is induced, taken into consideration the characteristics of beams, columns, and important load-bearing members in a particular structure. So, pushover analysis is going to basically tell us, corresponding to the loading condition, how the response of a particular structure, and when we are talking about response, primarily, we are interested in the displacement response of the structure. So, it is the most popular as well as the simplest method to perform nonlinear analysis, as well as for corresponding to dynamic conditions. So, it is also a static nonlinear method, where you take approximately how much is the earthquake loading condition into account, and then perform the analysis to find out how the storey displacement or the overall displacement at the top, if you are talking about the entire building, how the rooftop displacement is changing. Primarily when we are talking about high-rise buildings, the displacement-based approach will govern the design. So, when we are going with pushover analysis, we have to take into account that with respect to the base here, how the rooftop displacement is changing under earthquake loading. Primarily static or uniform amplitude of earthquake loading is applied, if you want to take into account the actual ground motion characteristics to understand the response of the building, we can go with nonlinear time historey analysis. So, there, you will take into account how the amplitude of ground motion is also changing throughout the duration of the earthquake shaking condition.

So, this does not take into account the dynamic or reversal nature of earthquake, that means even if you are going with nonlinear analysis, it will take into account the static part, that means the amplitude of loading is not going to change with respect to time, it is going to remain constant with respect to time, and then you apply it in terms of, primarily, in terms of base here, as given in IS 1893 code, and then you can understand the response of a particular structure or response of a particular building. So, it does not take into account the dynamic characteristics or reversal of loading conditions with respect to the time for which the earthquake shaking has been prominent. It generally considers monotonic load, which is applied to the base of the building.



So, consider this as a critical example of a particular building where you can see this is a building at a particular site, ground plus 3, which is given over here, and subsequently, we can go with more similar analogies, which we will be drawing for this particular figure. So, here we can see this is a building at a particular site. The building, based on maybe, you can say, if you are referring to the zonation map, then, corresponding to which particular zone the building is located, then you will have other factors which will come into account, and finally, you will be getting a value of base shear (V_b). That means whenever earthquake loading is applied to a building, finally, in the lateral direction, because vertical direction earthquake shaking will be dominated or will be significantly substantiated by means of gravity. So, prominently, earthquake loading condition in the lateral direction will be more demanding as far as the capacity of the building is concerned. So, V_b is going to be the base shear, which is corresponding to earthquake loading, and this earthquake loading, if you are going with the zonation map, again, the zonation, average horizontal design coefficient is given. One can refer to those and can determine the value of base here, again referring to the formulation given in the codal provisions. If you are going with seismic hazard analysis, that means you will be taking into account the site for which, suppose, this building is a very important building or nuclear power plant is there, then, in addition to codal provision, you can go with site-specific studies. You collect information about past earthquakes which have happened in specific radial distances, how much that radial distance will be there, that you can check with the corresponding code.

So, 300, 500, even 1000 kilometers radial distance, if it is required, so within 1000 kilometers radial distance, how many earthquakes are known so far which have happened in the past, starting with the very recent earthquake where ground motion recording has started, then you can go with those earthquakes for which isoseismal maps are available, where you can report that depending upon the damage scenario. Where, if we can recall the earlier lectures, every time there is damage during a particular earthquake, this particular damage characteristic you can, with respect to the damage scale or intensity scale, and corresponding to which level of intensity your site experiences damage, is matching that particular intensity value, you can assign. So, similarly, we will be having a lot of isoseismal maps corresponding to those earthquakes for which ground motion records are not available because such earthquakes had happened much earlier than the recording of ground motion had started. Then, you can go ahead with referring to older catalogs, which might be talking about some earthquake that happened maybe in 1500, 1200, 1100, and even before 1000 AD. So, there are certain catalogs also one can refer to, which have also been generated or created over the period of time, taking different literatures suggesting some scenario of damage very much similar to what generally in today's world we are experiencing during a particular earthquake. So, based on these also, people have found out, which is documented also, that during a particular year, maybe in 1100, 1200, something similar to waves or maybe material damages at multiple locations in a particular epicentral region were reported, which was very much identical to earthquake occurrence.

Then, you can also gather information about historic earthquakes based on paleo-liquefaction investigations. This we had discussed when we were discussing about firstly active and inactive faults. So, whenever we are going for active faults and to demarcate the boundaries or possible location again, we have to go ahead with what are the geomorphological and geological features available in a particular region, which directly or indirectly indicate that there might be a possibility of a particular fault in a particular region, which might have triggered an earthquake in the longer run. So, maybe once, maybe one earthquake, maybe 2,000 years back, might have happened during that particular fault, or you can go ahead with paleo-liquefaction investigations, which were also discussed in earlier lectures. So, paleo-liquefaction investigation, we will have to search for seismic sites, which will give an indication about some features which were created during historic earthquakes, maybe 700 years back, maybe 1500 years back, and remain intact because once the pore pressure dissipation, if you take into account sand dikes or sand blows after pore pressure dissipation, which had happened during a particular earthquake, these features or at least some portion of these features remain intact in some layers available beneath the ground surface.

So, again, based on that also, you will be getting more information about historic earthquakes. So, collectively, if you are going to determine base shear based on hazard analysis, we will be having historic earthquakes based on paleo-liquefaction investigation, we will have historic earthquakes based on well-established catalogs, we will have additional earthquakes again in terms of intensity maps or damage maps, then we will have earthquakes that happened very recently in the last 50, 60, 70 years, for which ground motion records are available in different parts of the globe. Collectively taking those into account and following the methodology which we have discussed in terms of deterministic and probabilistic hazard analysis, corresponding hazard values can be determined for a particular site of interest. Again, rather than using zonation factors, which are given in IS code, one can, if you are going with site-specific studies to determine the base shear, you can refer to these seismic hazard values. Always take into account that whenever we are going with seismic hazard values and try to determine the value of base shear, make sure that the condition at which your building is located in order to find out the base shear and the condition for which the particular seismic hazard values are given should correspond to the same site condition. Generally, the seismic hazard maps are available corresponding to bedrock condition, so how that bedrock condition, ground motions, or seismic hazard values will be altered reaching to the same level where base shear is being calculated for these kinds of analysis has to be understood firstly. Accordingly, the seismic hazard values will be modified and can be taken into consideration when you are going with scenario-specific because now you will be getting the value of base shear corresponding to some scenario, which can be the worst scenario if you are going with deterministic hazard analysis. If you are going with probabilistic hazard analysis, then again, corresponding to 10% probability of accidents in 50 years or 2% probability of accidents in 50 years, you can find out how much the seismic hazard values take that into account, ensuring that both are corresponding to the same site condition. You can utilize the formulations given in IS code to determine the value of base shear.

So, generally, here we are trying to assess how much is the arbitrarily applied or expected to be applied base shear at the building because of an earthquake or take into consideration the seismicity of a region. This base shear is basically an indication of or a quantification of loading which has been generated in some form because of the earthquake and is applied at the base of this building. From here, the building will be taking the shearing and it will be transferred to different stories in terms of storey shear, which are given over here as Q1, Q2, Q3, Q4. So, at different levels, as you are going above the ground floor, depending upon the stiffness, there will be some distribution of storey shear, which will be actually the loading you are getting because of the base shear or which is a measure of earthquake loading condition. The earthquake happened somewhere and was transferred to the building in terms of base shear, then Q1, Q2, Q3, Q4 are the actual shear applied at each storey, which, in order to prevent damage to the building, these storey shears (Q1, Q2, Q3, Q4) have to be actually resisted by the beams, by the columns which are available, or additional members are there to raise this shearing, so those members should also be taken into consideration. So, firstly, you will determine the arbitrary base shear or the base shear which will be applied, taking maybe the seismic zonation factor or site-specific seismic hazard study. So, base shear is basically quantification of maximum lateral force that will occur or that will be applied, that will be mobilized due to seismic ground motion or seismic activity in a particular region, and this maximum base shear will be applied at the base of your building. This base shear, if you are referring to Indian Standard Code 1893, came in 2002, and subsequent revisions are also there, so we can find out this base shear as V_b.

$$V_b = \frac{ZIS_a}{2Rg} \times W$$

That is base shear, which is given over here also. This is the same value of base shear which is shown in the figure also, and same is shown in the equation also. But overall, based on the design response spectra which is given in Indian Standard Codes, it is basically referring to this particular equation. You are going to get how much is the demand expected from your building corresponding to a given earthquake loading condition.

So, zonation factor or zone factor is the factor to obtain the design spectrum depending upon the perceived maximum seismic risk characterized by a maximum considered earthquake. So, directly we can take corresponding to different zones also. The maximum considered earthquake can also be found out in the zone in which the structure is located. So, you have to find out which particular city or which particular zone your building is located. Accordingly, one can refer to Table 2 of IS 1893 2002 and get the value of the zone factor. Similarly, the importance factor (I) is the factor used to obtain the design seismic forces depending upon the functional use of the structure. The structure can be the same, but depending upon the functional use of the structure, depending upon the hazard consequence in case the structure undergoes failure. So, there is a routine building where people are living, and there is a nuclear power plant where radiations are contained. Definitely, both will have drastically different sets of consequences in case of failure. So, if a routine building undergoes failure, there might be casualties restricting primarily to the intended users, and that will be the corresponding damage because of that particular building. But if you are dealing with a nuclear power plant, if there is a leak of radiation, then it will be a total catastrophe. So, definitely, the importance of those structures will be much higher in comparison to the routine buildings.

One can refer to Table 6 of IS 1893 and find out what will be the importance factor corresponding to the building you are dealing with. The response reduction factor (R), as I mentioned earlier, is a factor by which the actual base shear that would be generated if the structure were to remain in the elastic limit is reduced. So, that means how much response should be allowed in the structure such that the component will remain in the elastic limit, and primarily it corresponds to the design basis earthquake (DBE). This is like the scenario in probabilistic hazard analysis corresponding to a given probability of exceedance in a defined return period. There are definitions to find out maximum periodical earthquakes, shape shutdown earthquake, and design basis earthquake. So, one can refer to the design basis earthquake. The value of the reduction factor can be found from Table 7 of IS 1893-2002, particularly for the Indian subcontinental scenario.

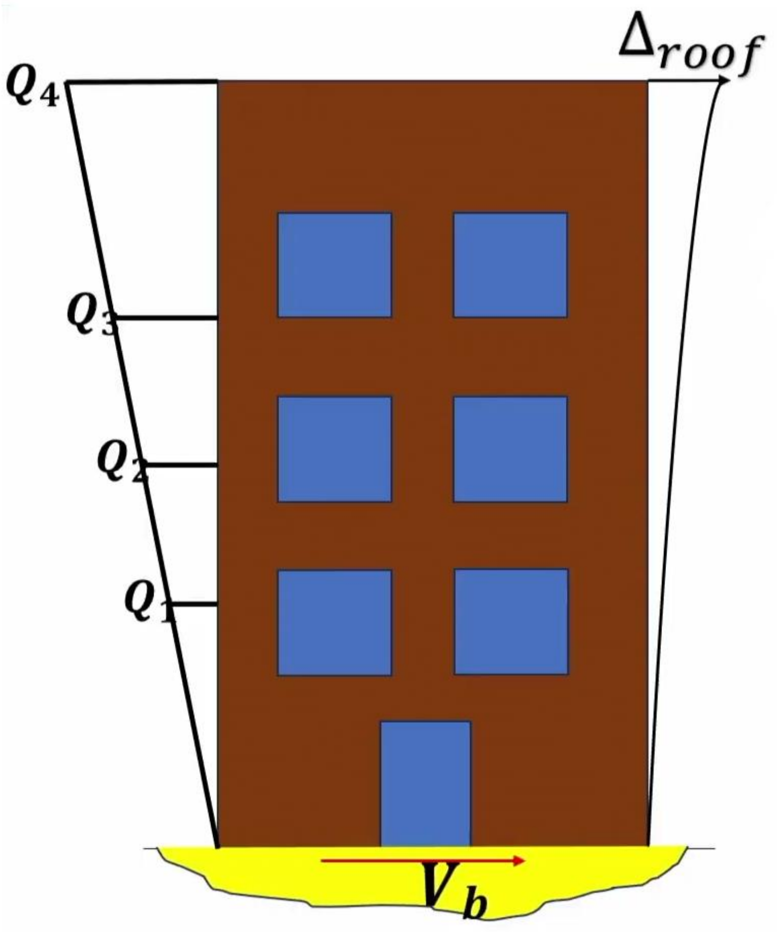
Then, the average response acceleration coefficient (S_a/g), as I mentioned earlier, has design response factors corresponding to the site conditions at which a building is located and corresponding to the natural period of the building. Firstly, you can pick up a particular graph, and then, on the graph, on the x-axis, corresponding to the natural period of the structure, you can draw a vertical line where this line is touching your appropriate graph, whether it is corresponding to 1, 2, or 3 types of site conditions. You can find out the value of the average response acceleration coefficient. Taking those into account, you can find out the value of base shear, and then, corresponding to base shear, you will go to Step 2: to distribute the base shear along the height. You have applied shear to the base, and then it is being imparted to the entire building considering the stiffness, which is changing across the height. The base shear will also be redistributed to different heights in the building, as shown over here. Then, depending upon the shear applicable to a particular height and the resistance offered by the members at that particular height, collectively, it will add some form of deformation from that particular height.

If you remember our discussion a couple of slides back, whenever we are going for pushover analysis, we are trying to find out, corresponding to the base shear which is applied over here, how much is the total displacement at the top of the building because that is a representation of the maximum response the building is going to show corresponding to a given base shear. So, you go with the distribution of base shear along the height. This distribution should be as close an approximation to what happens during a particular earthquake. So, we have a well-established formulation based on which we can distribute the base shear to different heights. Now, if you are going with nonlinear analysis, or if you are considering that this particular building can be approximated to different numbers of lump mass systems, when these lump mass systems are exposed to external loading conditions, then, going ahead with our basic understanding with respect to a single degree of freedom system or multiple degrees of freedom system, we know that depending upon the frequency content or harmonic motion present in your external loading condition and how many degrees of freedom are available in a particular building, you can have approximately some fundamental mode as well as higher modes in which the building is going to respond, or different stories are going to respond, or the locations that have the inertial force or where the mass is concentrated at different stories of a building. Definitely, these masses will undergo deformations, and these masses will undergo some movement in terms of the building's response to the external loading condition.

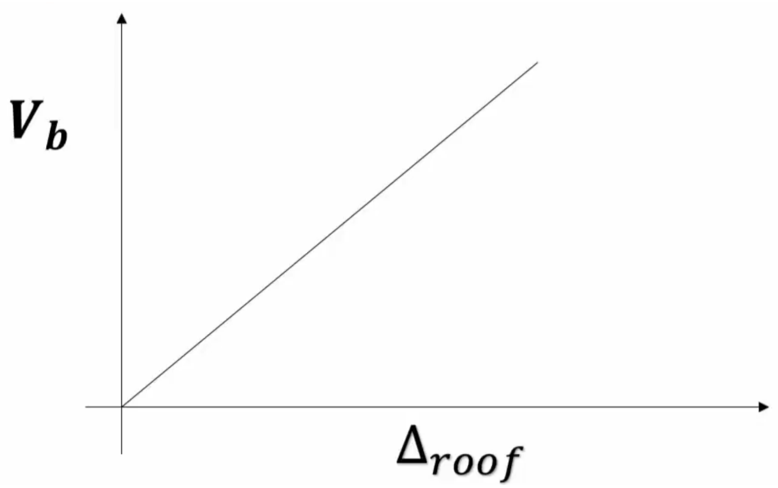
So, if we look into the governing equations for a single degree of freedom system, we can find out how much the natural frequency of the building is, both in the case of a damped as well as an undamped system. Similarly, if you are going with multiple storey buildings, we can approximate or we can approximate the response of this building with respect to an MDOF (multiple degrees of freedom) system. Taking eigenvalues and eigenvectors, we can find out what the different natural frequencies are, and corresponding to these natural frequencies, how the mode shapes of these buildings are going to be, corresponding to a given earthquake loading condition or corresponding to a number of sets of harmonic motions, depending upon the choice of the analyst.

So, certainly, we will be having the fundamental mode, which might be giving the best approximate mode shape with respect to the actual response of the building during a particular loading condition. There can be higher modes also, depending upon what sort of analysis you are doing here and what mode you are targeting to find out. So, hence, the distribution is in proportion to the fundamental mode. If you are only focusing on the fundamental mode, the distribution of base shear will be in proportion to the fundamental mode or what the contribution of each of these stories' stiffness is in order to govern the fundamental mode or mode shapes corresponding to the fundamental mode. So, based on which, you can find out the storey shear, taking the base shear into account, taking the stiffness values into account, the mass values, the stiffness values, and even the damping values. One can go for the solution of the multiple degree of freedom system's governing equation.

Pushover analysis is required, which is also called single-mode analysis, where, corresponding to the given base shear, you will try to find out which different beams and columns are going to resist the applied base shear. So, what will be the response of those important components whenever this storey shear of Q1, Q2, Q3, are applied to each of these members? So, what actually will happen if you go ahead with all the members simply providing resistance corresponding to shear and base shear? Then, you can see that whatever base shear you have applied, there is a corresponding displacement at the rooftop.



So, conventionally, if you are going with the linear method, that means you are considering that all the material which is available to offer resistance to this external loading condition will only offer resistance within the elastic limit. Or, whatever base shear you have applied, the loading in the material will be ensured to remain within the elastic limit of the material properties. In such a case, you can find out that as you go further from the base shear or as you go higher in the building, the displacement value increases. So, you can find out, based on your pushover analysis, a plot between base shear (how much shear you have applied) and how much external loading condition corresponding to the seismicity you have applied at the base. Subsequently, you have found out the value of storey shear, and corresponding to the storey shear, you have found out, based on linear analysis, how much the displacement will be at a particular storey and subsequently at the top of the building.

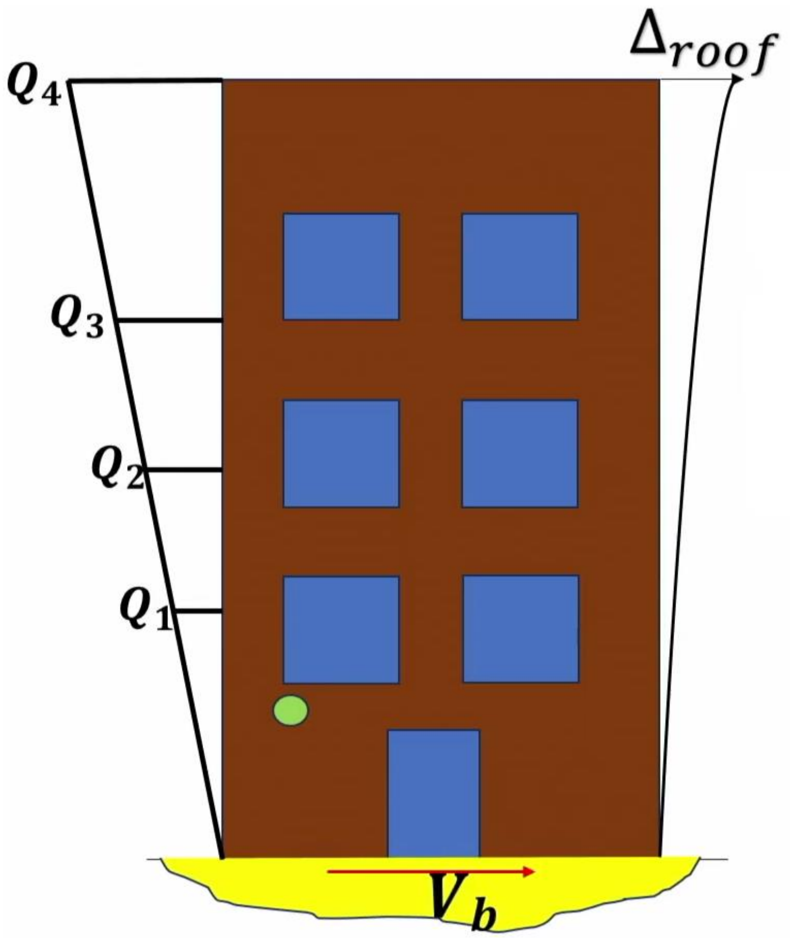


So, based on pushover analysis, in the initial state, you will find out how the variation in rooftop displacement is happening as a function of change in the base shear values. Always keep in mind, this particular plot is corresponding to the linear elastic deformation of critical components of this particular building or any particular component of this particular building. Take into account that these components are loaded only up to the elastic limit, so whatever deformations are there in the building, you remove base shear and then the material will come back to its original position. We are not taking, at this stage, any plastic hinge formation or any kind of yielding in any particular material.

But in actual, primarily, if you are talking about earthquake loading conditions, firstly, it is reversal in nature; secondly, it is dynamic as well as it will be applied over a period of time. So, it may be depending upon what is the duration of shaking, at least that is the duration in which this particular loading will be active on a particular building. So, definitely, there will be, because of this cycle of reversal of stresses, there might be some degradation in the material characteristics if you are going with nonlinear analysis or if you are taking the hysteresis loop, which is defining the degradation in the material characteristics when the material is subjected to a given earthquake loading condition. So, what will happen over here, particularly in this particular case in actual, there will be formation of plastic hinges. There will be some components of beams and columns which will undergo yielding; that will, and so, corresponding to that, initially, you have applied some base shear, but correspondingly, once you do the linear analysis, you will find out impairing the nonlinearity also into account because that is the actual way in which the response has to be there.

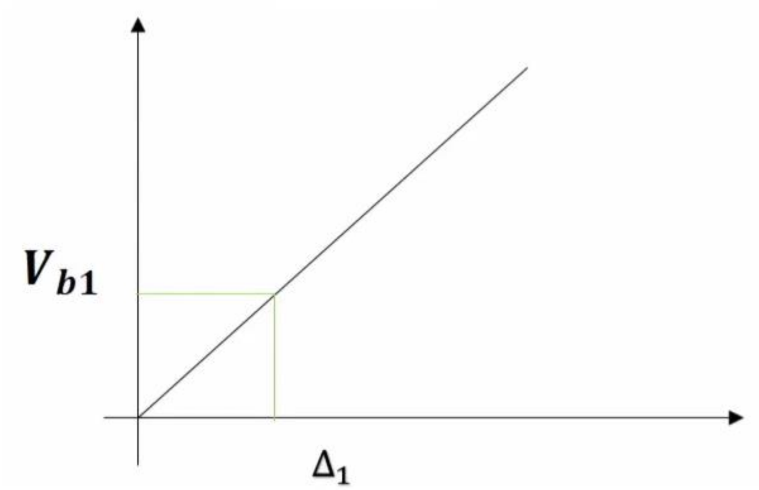
So, what you will do, the plot of base shear versus rooftop displacement, which was shown as linear, was primarily because we have taken the linear method of analysis. But if you are going with nonlinearity, because all the components which are offering resistance are actually offering resistance in a nonlinear nature. So, base shear in such a case cannot go on increasing with the rooftop. So, there cannot be an increase in the rooftop displacement with an increase in the base shear because if you keep on increasing the base shear, definitely your strain energy as well as the shear strain, which will be imparted to different stories, will also change. When the shear strain level is changing, definitely, we cannot ensure that for each value of shear strain, whether it was too low, whether it was intermediate, or whether it was too high, definitely, the linear component will not be ensured as given in the previous plot of base shear versus rooftop displacement. So, we have to take into consideration the nonlinear nature. Maybe we can approximate with respect to the approximate degradation properties, but certainly, that way has to be taken into consideration because when we are going with understanding the building response, definitely, we know that earthquake loading conditions are going to induce a significant level of nonlinearity in the material or the material when it will be subjected to loading because of earthquake-induced waves, certainly that will take the material to the nonlinear part. So, that part will be taken into consideration. As a result, when we take the nonlinearity of important components into account, there will be yielding in the material. As a result, there will be formation of plastic hinges, so one can apply the demand.

So, initially, you applied the base shear and found out the storage shear, and corresponding to that, you found out rooftop displacement, taking only the linear part. Now, taking the nonlinear part, we can again go for finding out the components which are undergoing failure and then we can find out the moment capacity.

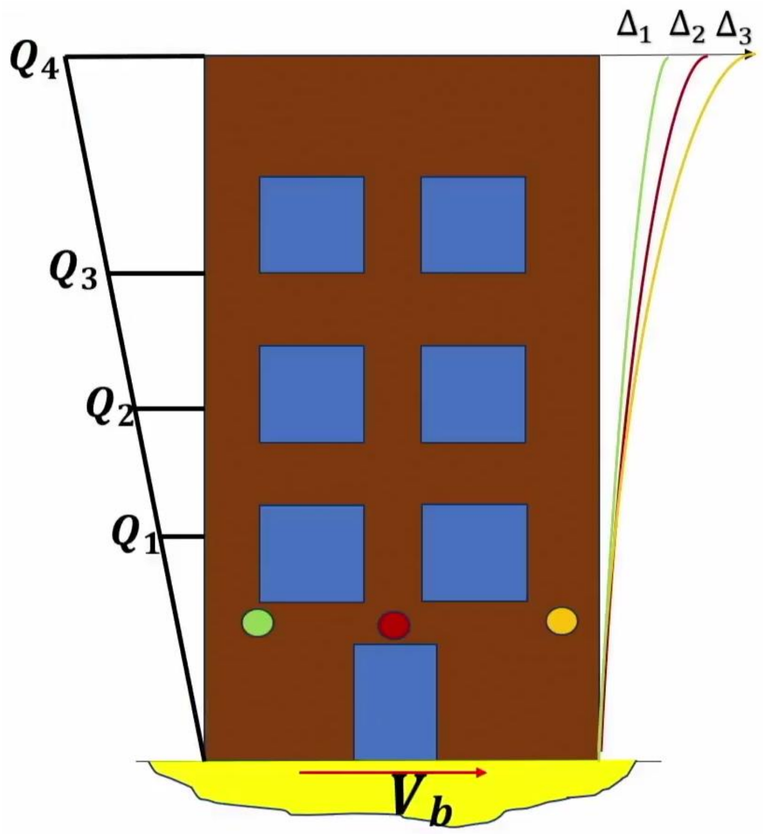


Suppose this is a point which has actually subjected to yielding; there is a first point which has subjected to yielding or there is formation of plastic hinges, so definitely, this component, this particular dot, when there is plastic hinge formation, definitely the moment capacity, there will be a redistribution. Subsequently, this will have an effect on the rooftop displacement. So, whenever the design capacity ratio is maximum, that particular point is an indication of the member which is yielding. So, this will go on in an iterative manner. You found out first, then again you go for the analysis, and you may find out another location in which the demand capacity has reached; that is an indication that the other member is also yielded, keeping the base shear the same but changing in the response of the material. The material is not only linear but subsequently, depending upon the shear strain mobilized in the material, it is also going to the nonlinear part. So, you continue this particular part, there will be plastic formation, plastic hinge formation at the location where the demand capacity has reached its maximum.

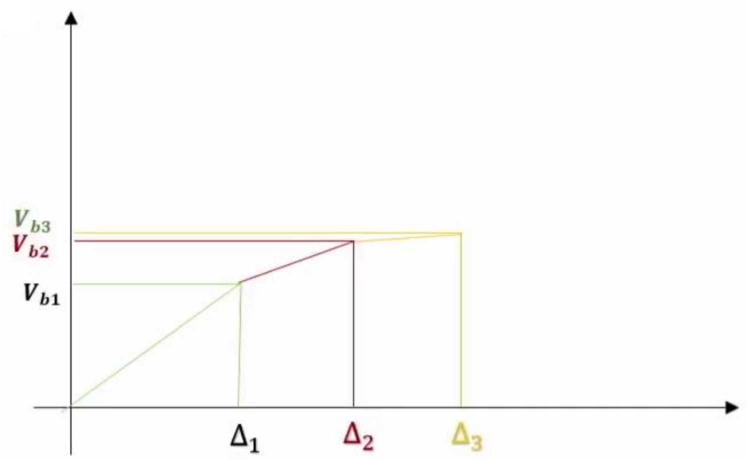
The base shear will be recalculated because every time there is yielding in the material, the resistance from a particular storage shear is going to change. Definitely, this is going to have a direct effect on your storey-wise displacement and subsequently the displacement at the top of the building. And remember, we are going to decide the damage characteristics of the building, primarily taken into consideration the capacity of the building in terms of rooftop displacement. So, pushover analysis is going to give us the capacity curve, which is in terms of rooftop displacement, how it is changing with respect to base shear. So, base shear is an indication of earthquake loading conditions, and rooftop displacement is a representation of the response of the building in terms of formation of plastic hinges at different levels all throughout the building height. So, this way one can get base shear and, corresponding to base shear, maybe first point of yielding, second point, and subsequently.



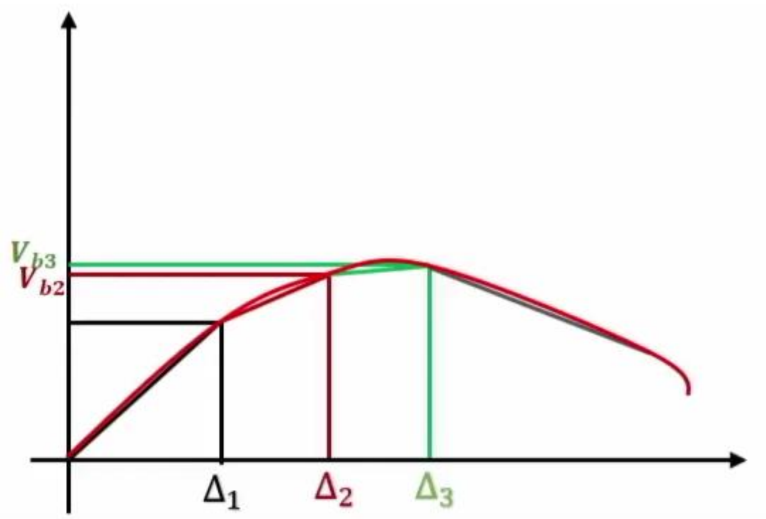
So, this is the first point of yielding. You will get to know that, corresponding to the first point of yielding, what is the deformation.



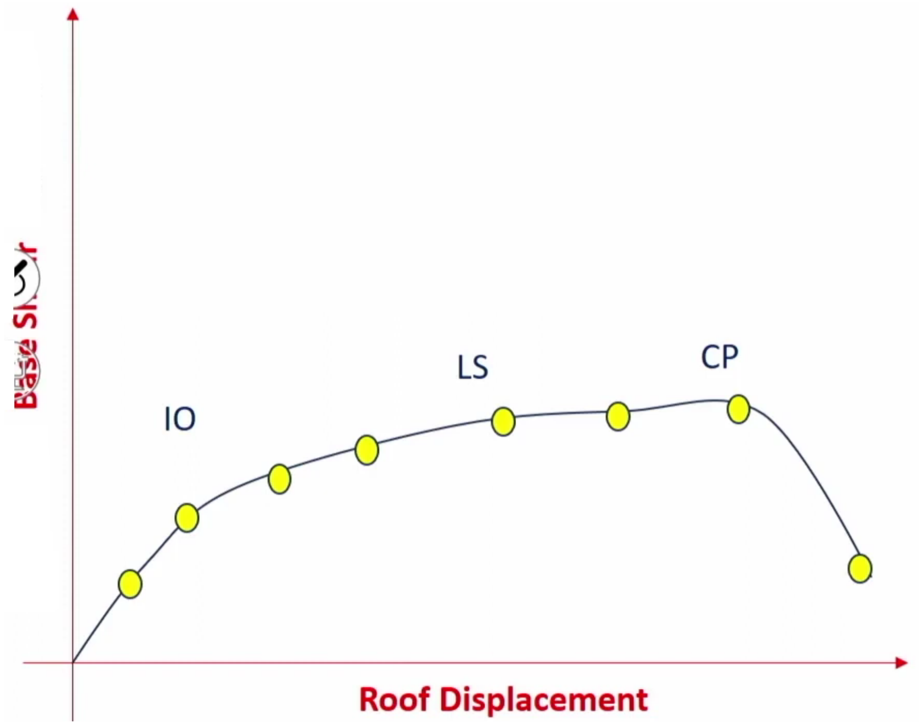
Repeat the same exercise, you will get more points along the beams and the columns which are undergoing yielding. Accordingly, the stiffness value corresponding to each storey will be revised, taken into consideration the points of plastic hinge formation. Again, there will be base shear and corresponding the response to each and every storey will be recalculated at the same time.



So, here we can see that, as plastic hinge formation has happened, the rooftop displacement, or the displacement you are getting at the top of the roof corresponding to applied base shear, will not remain as linear because of more and more hinge formation. That means the response of the building will significantly reduce rather than the same response which was shown for linear analysis. So, this is shown over here, so we can see delta 1, delta 2, delta 3. It is basically in an iterative manner, you are finding out, as you keep on increasing more and more base shear, there will be an increase in the locations of plastic hinge formation, and subsequently, that will have an effect on your rooftop displacement values. So, based on this curve, which was base shear versus rooftop displacement, based on nonlinear analysis, but only taken into consideration the formation of the hinges, that means we are not so far taking into consideration the duration of loading. So, this continues until all the beams and the columns are developing plastic hinges. That means this is the actual response, nonlinear response of your building for an applied base shear. Now, in addition, we will also take into consideration that there is a building, and whenever there is an increase in the load, there is gravity load also which is there applied to the building. So, which will also prevent too much of displacement going here and there with respect to the mean position of the building, so that will have a negative stiffness, which will be imparted to the building. So, taking the gravity load as well as the nonlinear response of the building, again related to pushover analysis, one can find out the capacity curve. So, overall curve, that means you will take into account the gravity load. You will also take into account how, with respect to base shear, the rooftop displacement is changing from storey shear alone.



So, collectively, by merging both the responses, we will get to get this particular plot, which is on the x-axis, you are having rooftop displacement, how this rooftop displacement is going to change from linear to nonlinear to nonlinear plus self-weight of the or the vertical load which is applied, and then corresponding to this is a function of how, with respect to base shear, your displacement value is changing. So, you can see initially the value was more, and as you are going to increase the base shear again and again, the rooftop displacement has shown significant reduction. So, this is going to be defining the capacity curve of a particular building. The loading condition was corresponding to the seismic design response spectra, which one can pick up corresponding to the zonation map, corresponding to the importance, and so on.

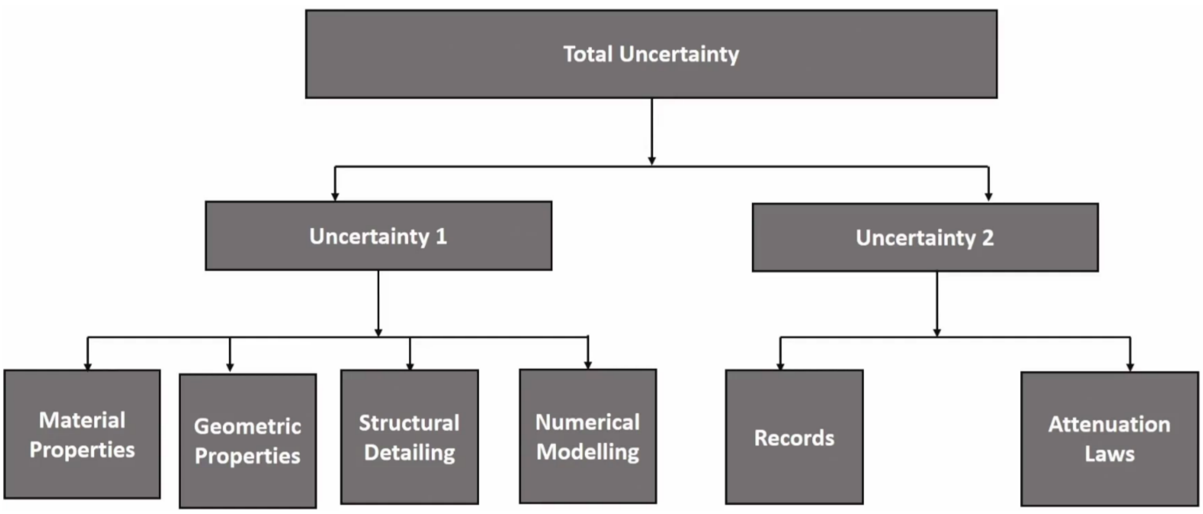


So, based on the capacity curve which we have defined so far, where base shear is there on the y-axis and rooftop displacement is there on the x-axis. Primarily this are basically the characteristics of the building for which you are trying to find out the demand during earthquake loading condition. Based on this, all stages of damages—so how you are going to define damages—again, you can refer to the codal provision, but you can typically find out three stages of damages. So, here, based on ATC, 1996 and FEMA, 1997, three stages of damage have been defined in this particular plot itself. Now, this is going to give you an overall capacity curve of your building. Depending upon what level of base shear you are dealing with, you can pick up whether your building should be, which because this plot is defined based on the response of the building. Now, when the overall plot is there, so this is going to be the locus of all the responses. Now, you can locate, keeping in mind what is the base shear your building is going to be exposed to—you can locate whether it is corresponding to immediate occupancy (IO). That means after repair and cleaning work, you can go and immediately occupy the building because the building is offering the resistance in terms of roof displacement much, much lower than the tolerable limit. Again, based on base shear, if you are reaching to LS, that means life safety, which indicates that till the time the building is exposed to the given earthquake loading condition, you can stay but not after that.

The third one is collapse prevention (CP). That means the building or the expected loading condition is such high that the corresponding rooftop displacement itself is very high, both from the strength point of view; even you can refer to the serviceability point of view. Finally, the observation with respect to the building is that the building is on the verge of failure or the verge of collapse. Certainly, you cannot occupy that particular building; you can take appropriate measures in terms of how to deal with the building, taking the finance which will be required and the importance of the building. So, this is going to be the capacity curve. We are having the capacity curve, which is going to be the response of the building, but actually, at a particular site, you are also having the demand curve. So, collectively comparing both the design curve and the demand curve, which is a characteristic of earthquake loading condition, and the capacity curve, which is the characteristics of how, for different sets of loading conditions, your building is going to respond, whether it is immediate occupancy, whether it is life cycle, or whether it is complete collapse. So, you can compare both the things. The demand curve is in terms of spectral acceleration versus the time plot, which is given in the Indian standard code. Also, using that, we can find out the demand, and the capacity curve is definitely the base shear versus rooftop displacement. So, identically, if you put both the curves one over the other, you call it the acceleration displacement response spectrum (ADRS). So, it is going to tell us what the relative comparison between the displacement of the demand curve is as well as the capacity curve or, overall, what is the performance of a structure that can be evaluated based on the acceleration displacement response spectrum.

Nonlinear analysis, as I mentioned, that whenever we are going with pushover analysis, whether you are limiting to linear or non-linear, you are not taking the ground motion characteristics completely as it is given during a particular earthquake. So, non-linear analysis, again, you can go with static analysis; you can target for a single mode, primarily the fundamental mode. Hence, it is only applicable to the building in which the fundamental mode is more dominating or having more contribution, but there can be conditions where, even in addition to the fundamental mode, one has to go with the higher modes. So, certainly, you have to take into account non-linear time history analysis, which will be actually the dynamic analysis, where multiple modes—not only the fundamental mode, but higher modes are also taken into consideration to find out the overall response of the building. So, here, you will take the complete time history of a particular building in order to decide the capacity of a particular building or the response of a building. If you are going with performance-based analysis or fragility curve development, you can go with a lot more time histories corresponding or acceleration time histories defining or approximating the seismicity anticipated at your site of interest during the given exposure period.

Again, with the plastic hinges, as I mentioned earlier; you can go with the complete hysteresis loop, which is going to give you that during the loading condition with respect to time, how the degradation in the material properties—whether it is at the beam level, whether it is at the column level, and subsequently at each storey level—it is going to change as far as the formation of plastic hinges is concerned. So, such things you can go with in non-linear time history analysis.



And there are certain details that have to be dealt with whenever we are discussing with respect to uncertainty. So, there are some uncertainties with respect to records, some uncertainties with respect to model material properties and dimensions.

$$P[ds_i\,|\mathrm{IM}]=\emptyset\left[\frac{1}{\beta_{ds_i}}\,ln\,\frac{IM}{IM_{ds_i}}\right]$$

$\emptyset$= Standard Normal cumulative distribution function

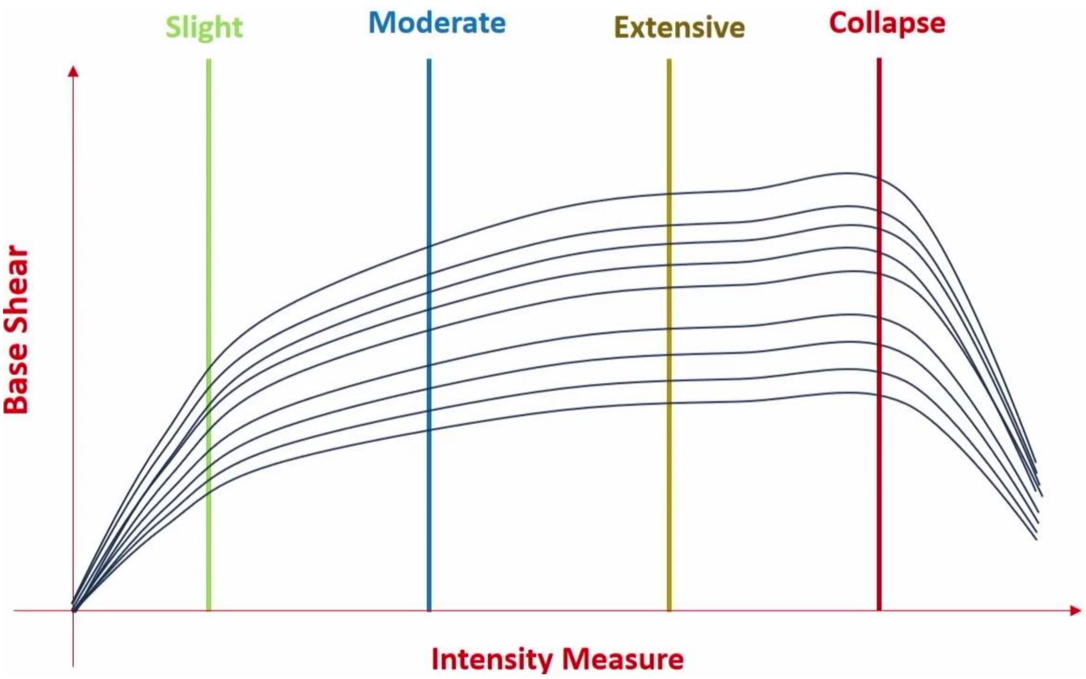
β_{dsi}= the standard deviation of the natural logarithm of the spectral displacement of the damage state ds.

ds_i= damage state

IM= Intensity Measure

IM_{ds_i}=Median value of the intensity measure at which the building reaches a certain threshold of the damage state (ds_i)

Fragility analysis is again going to give you an understanding or correlation between how the damages are correlated. So, I am not going to go into much detail about this particular part because this is just to give you an overview. So, fragility curve is basically a continuous representation of the probability of a particular level of damage with respect to earthquake intensity measures. So, as the intensity of the earthquake is changing, what is the probability of failure, how it is varying, so that for any expected level of ground shaking, which is likely to be experienced by your building, whether it is during design basis earthquake, maximum credible earthquake, or any specific scenario earthquake, you can have an idea about what is the probability that the damage will exceed a particular user-defined or codal provision-defined state.



So, you can see over here just an idea. Based on the capacity curve, also you can define the damage in terms of intensity measures. So, this is the fragility curve. You can decide slight, moderate, extensive, and collapse. So, once you are having the fragility curves, you can refer to this and find out. Generally, you can go for fragility curve analysis, taking a lot of analysis, changing the ground motion characteristics, and then you can come up with these fragility curves. So, with this, I have come to the end of this particular discussion. That means, what is the meaning of seismic vulnerability, and this subsequently can be carried forward to go ahead with risk assessment analysis. I have given some overview about what is risk, and once you have detailed information about the intended users for a particular building, you can continue with the risk assessment.

So, overall, this was about part 3 of seismic vulnerability and risk. So, thank you, everyone.