Conceptual Seismic Design of Buildings

A Resilient Future: Science and Technology for Disaster Risk Reduction

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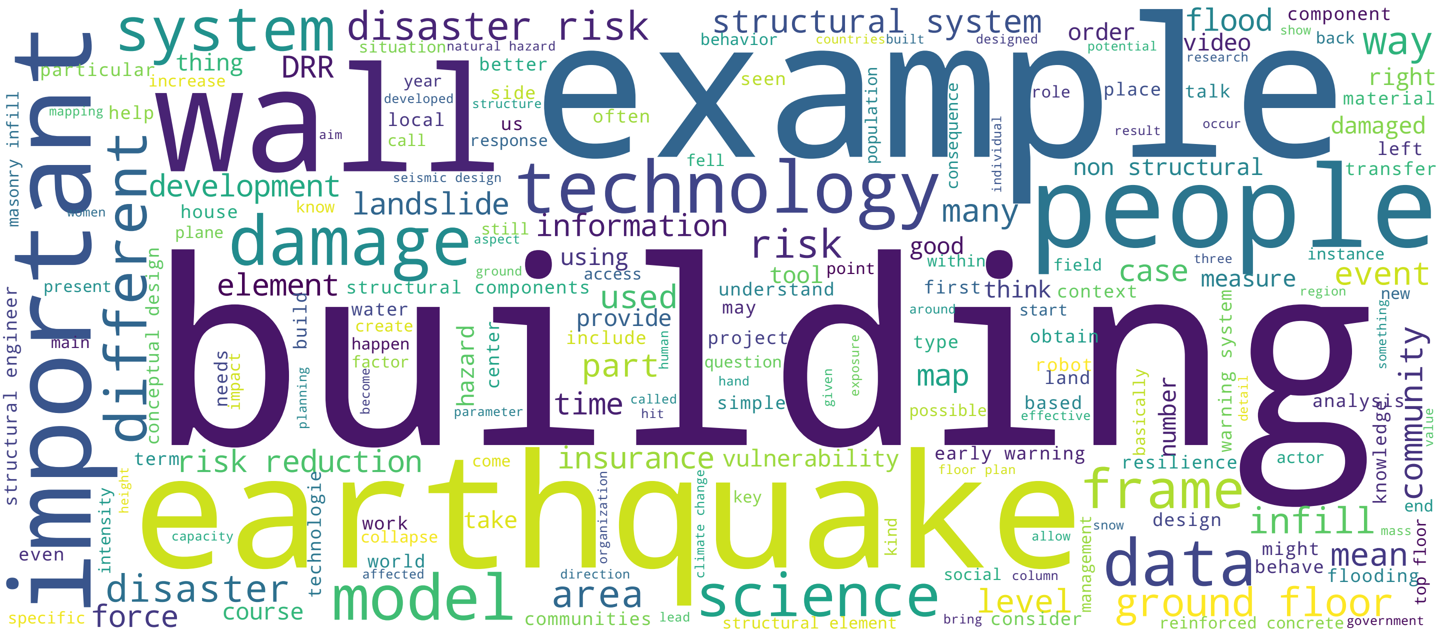

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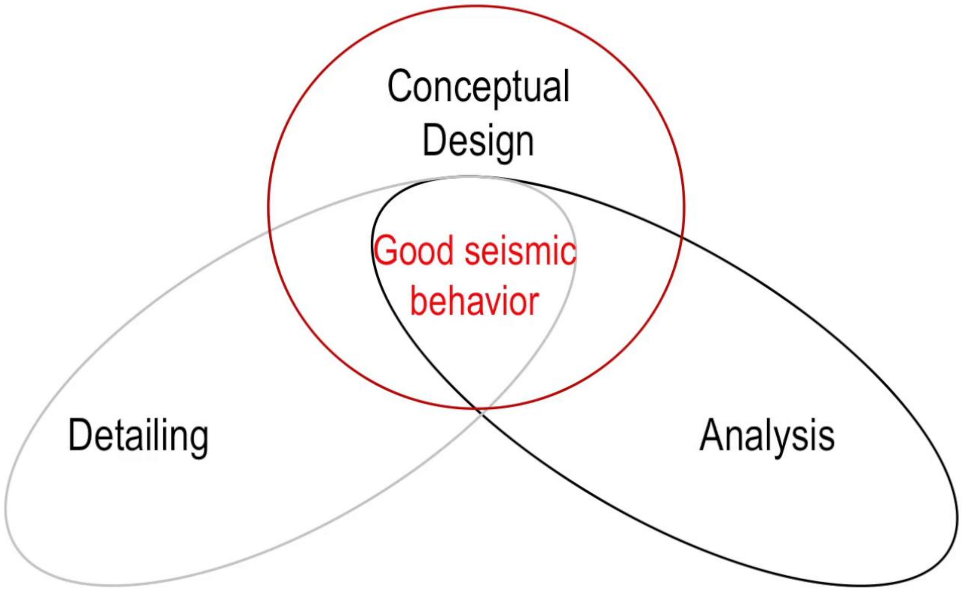
Video

Introduction: Factors ensuring good seismic behavior



A Resilient Future: Science and Technology for Disaster Risk Reduction

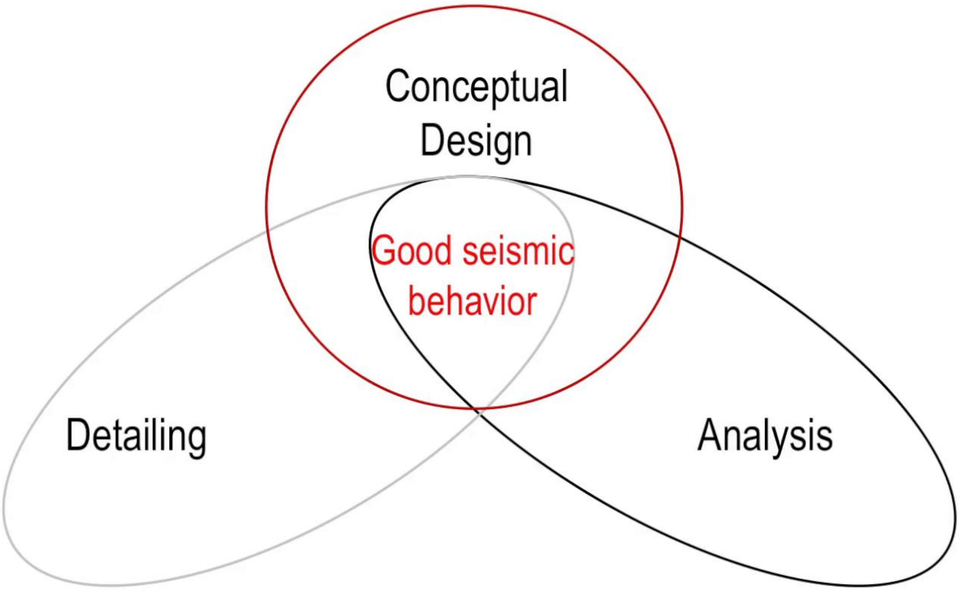
Hello. My name is Katrin Beyer. I'm a structural engineer, and I'm the head of the Earthquake Engineering and Structural Dynamics Laboratory at EPFL. In my research group we are studying how structures perform during earthquakes and we develop tools for predicting their performance. Today I'm going to talk to you on how we can design structures in such a way that they behave well during earthquakes. It is important to remember that not the earthquake itself kills people. If you're in the field during an earthquake, it is rather unlikely that you're injured or even killed. Most people die because man-made structures, such as buildings and bridges, collapse. It is therefore in our, the structural engineer's hands, to protect the people. This lecture is a first brief introduction to seismic design of buildings. Obviously it cannot replace a five year degree in civil engineering. The objective is really to give you a first idea about some points that need to be considered when designing a building to withstand an earthquake. What I'm presenting is not how to prove by calculations that a building is safe for a seismic hazard, I will be talking about the conceptual design.

Notes

Summary

0m 03s

Introduction: Factors ensuring good seismic behavior



(1)

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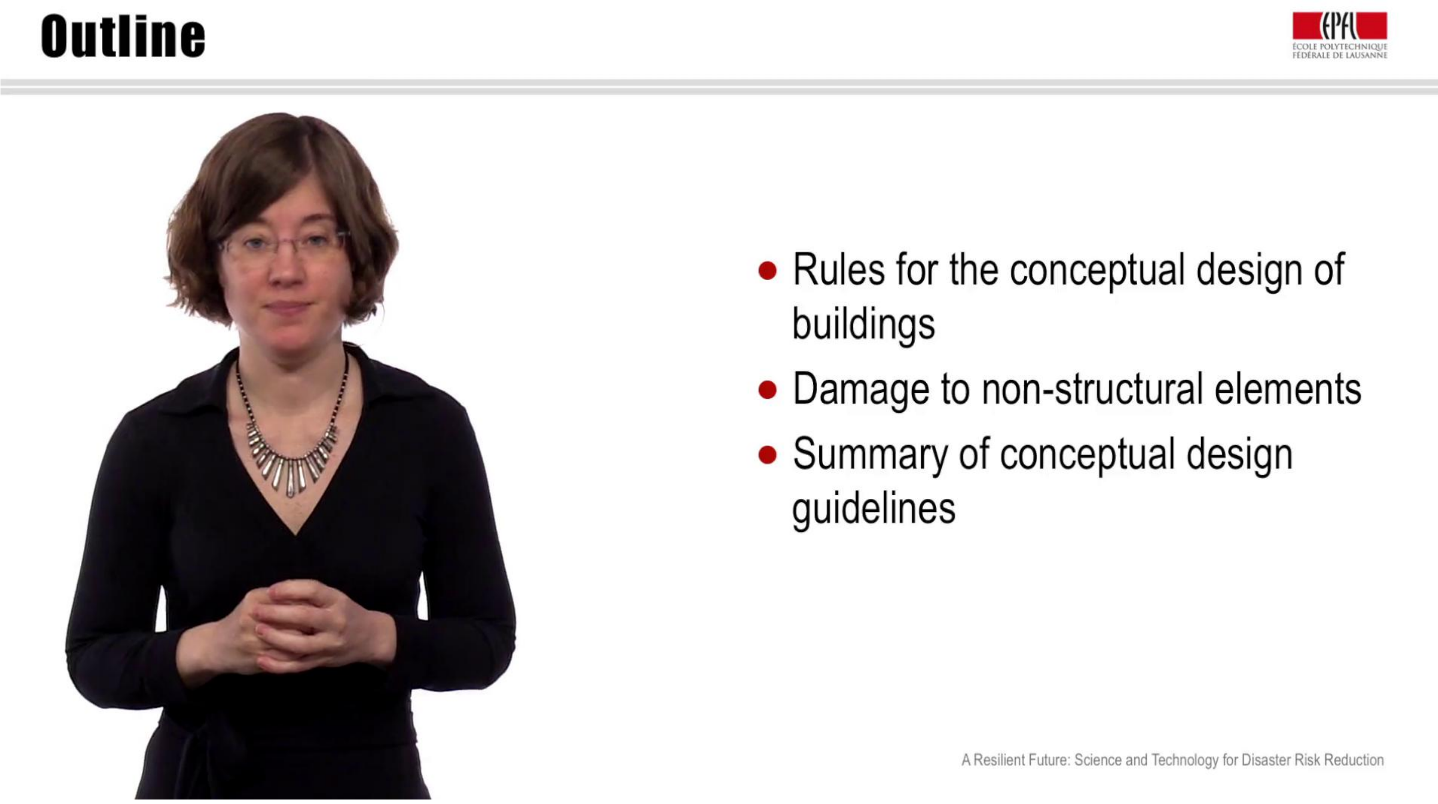
This is really the first phase of our design. So, for example, where we decide which structural system we are using for bracing the building. In order to really obtain a good seismic behavior, there are two other factors that are really important. So we also, of course, need to do analysis and you need to detail our structural member in such a way that they behave well. These two parts, this is really the task of the structural engineer. But for the conceptual design, it is really, very important that the structural engineer and the architect work very well together so that we, in the end, have a building configuration that suits the structural and the architectural requirements.

Notes

Summary

1m 14s



So this presentation starts with some general rules for the conceptual design of buildings. Then we will look at damage to non-structural elements, these are elements that are not important to carry the loads during an earthquake, but they can be damaged nevertheless. And then we will conclude with a summary of the main points.

Notes

Summary

1m 54s

Conceptual seismic design

Bachmann, H. (2003) «Seismic conceptual design of buildings – basic principles for engineers, architects, building owners and authorities», Federal Office for Water and Geology, Bern, Switzerland

(2)

A large part of this presentation is based on the booklet by Professor Hugo Bachmann: "Seismic conceptual design of buildings," which has been translated to many languages and is available online. It's an excellent introduction to the conceptual design of buildings.

Notes

Summary

2m 17s

Conceptual seismic design

Choice of structural system and construction material

Reinforced concrete frame

Reinforced concrete walls

Other structural systems

- Walls coupled with deep beams
- Wall-frame structures
- Braced frames

Construction material

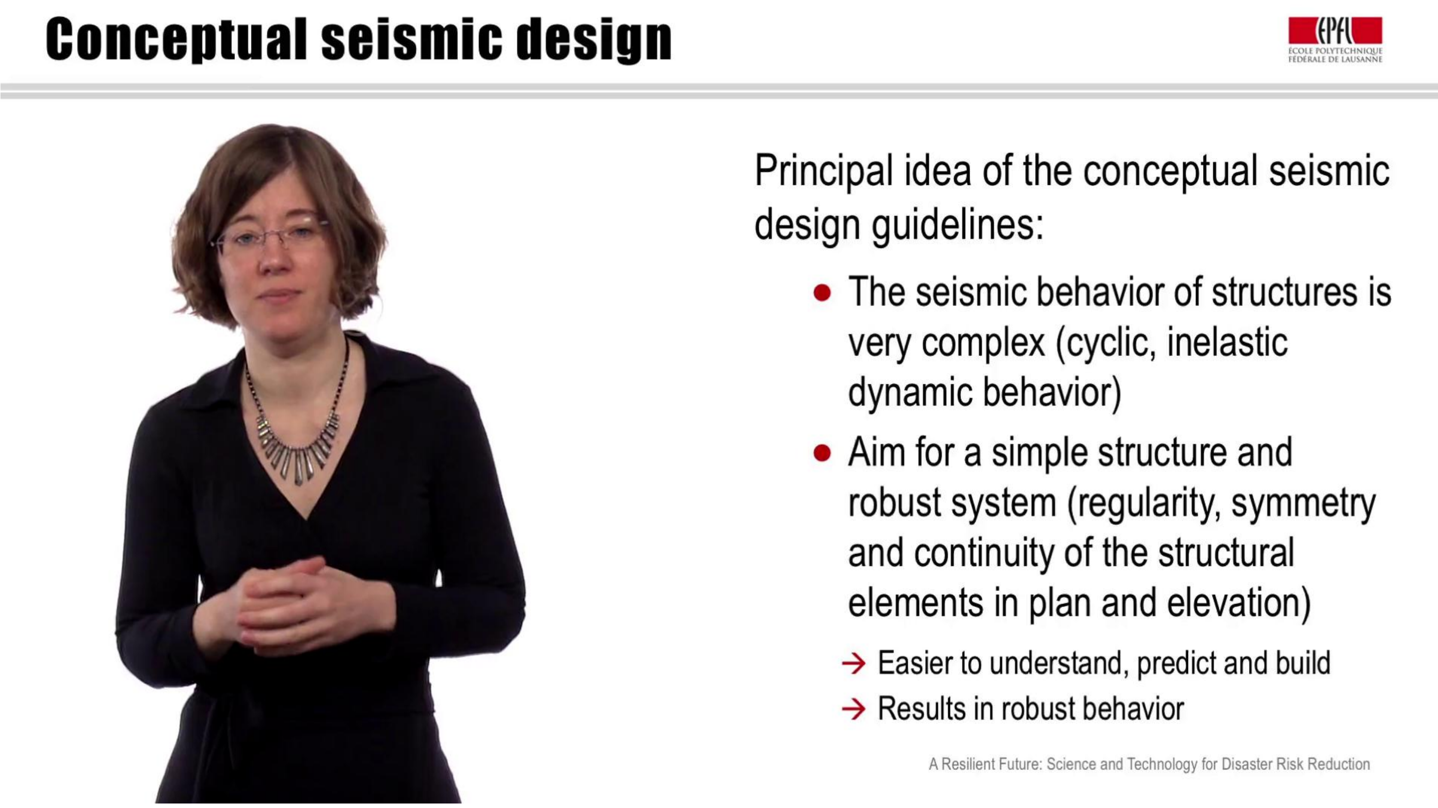
- Reinforced concrete
- Steel
- Timber
- (Masonry)

The first step of the conceptual seismic design concerns the choice of the structural system. Many different systems can be chosen. The most common ones are structural walls, or frames. Which of the system is the most suitable one depends within the height of the building and the use of the building. Typical construction materials are reinforced concrete, steel, and timber. All of these materials can behave well during earthquakes, provided they're designed in such a way that the structural elements have a sufficiently large space and capacity. Masonry can behave well if it's reinforced. Also in countries of low seismicity, unreinforced masonry buildings with stiff concrete slabs might be okay, however stonemason buildings, like they were built in the past, or adobe masonry structures with flexible timber floors are really among the most vulnerable structures during earthquakes, and often cause large number of casualties in the event of an earthquake.

Notes

Summary

2m 31s

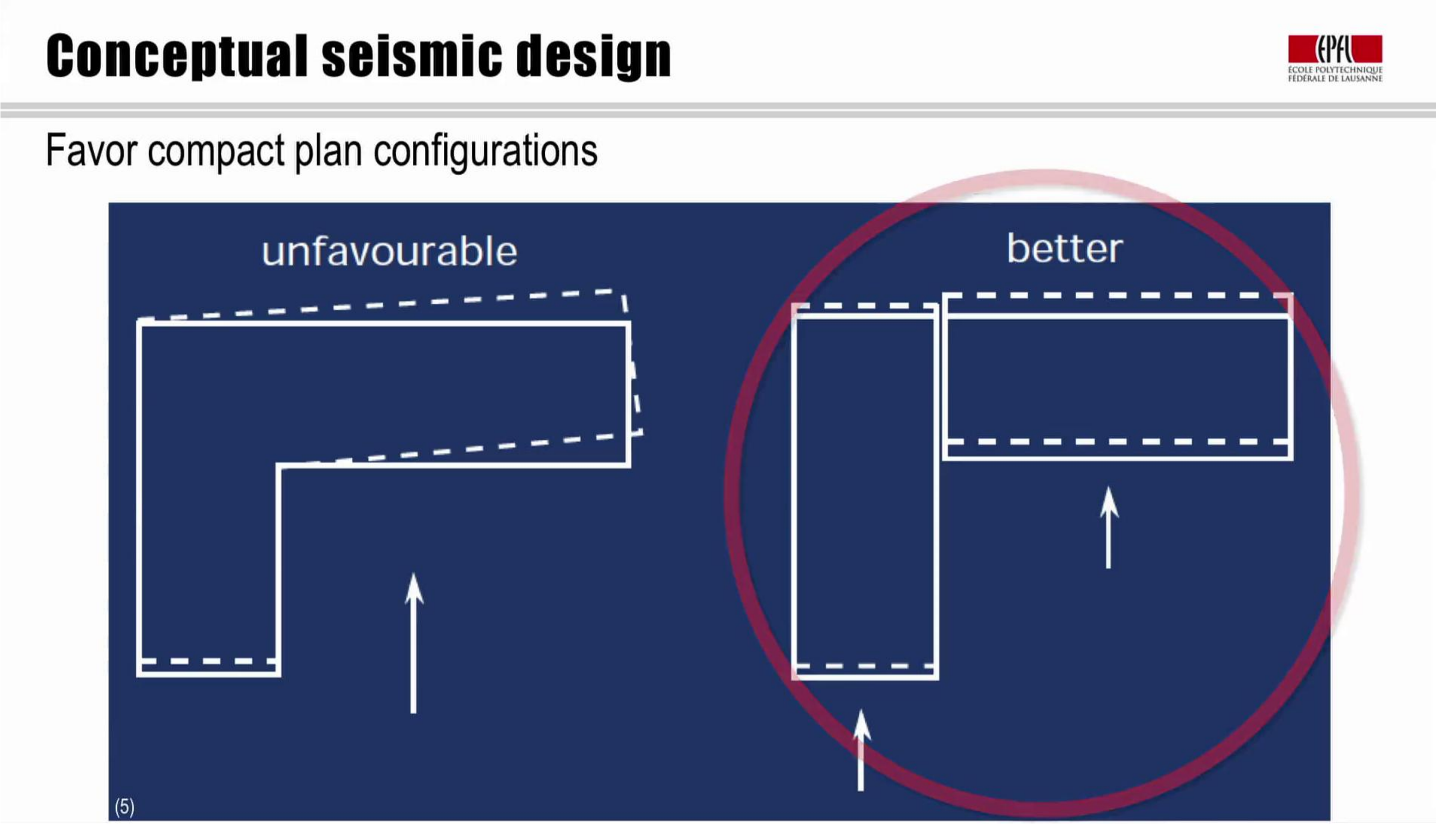


Independent of the choice of the structural system, one should aim for a simple and robust structural system. That means that for a system that is relatively regular in plan and elevation. And also for a system that has some redundancy. The behavior of a building is really a very complex affair during an earthquake. The building is shaken in all directions. The loading is cyclic, goes back and forth, and during a large seismic event which drives the seismic design of all buildings, you also expect the buildings to undergo inelastic deformations. Simulating this behavior with computers is today, still a very challenging task. Moreover, we never know exactly how the next earthquake will look like. For this reason it is really very important that we choose a structural system that is robust and simple so that it is easier to understand, predict, and build.

Notes

Summary

3m 28s



To achieve this goal, we should aim for a simple and compact floor plan configuration. For example, if we have such an L-shaped floor, like here on the left, it might be better to split it into two rectangular floors, like here on the right.

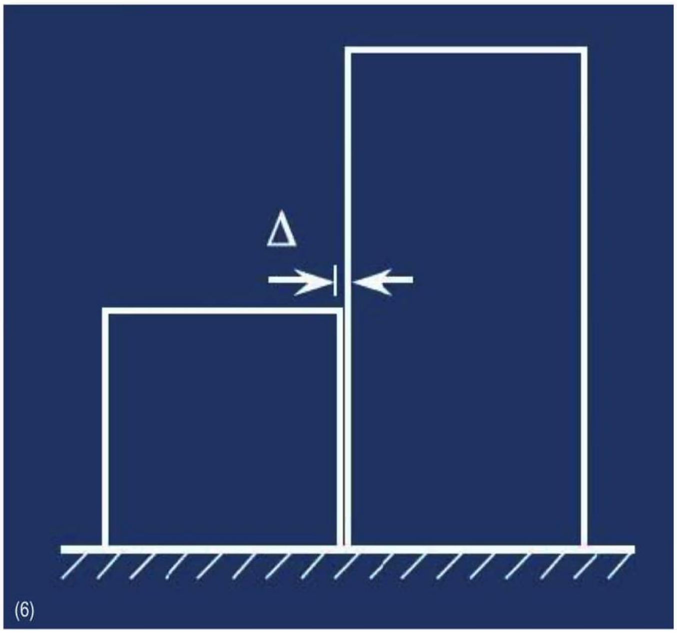
Notes

Summary

4m 28s

Conceptual seismic design

Separate adjacent buildings by joints to avoid pounding

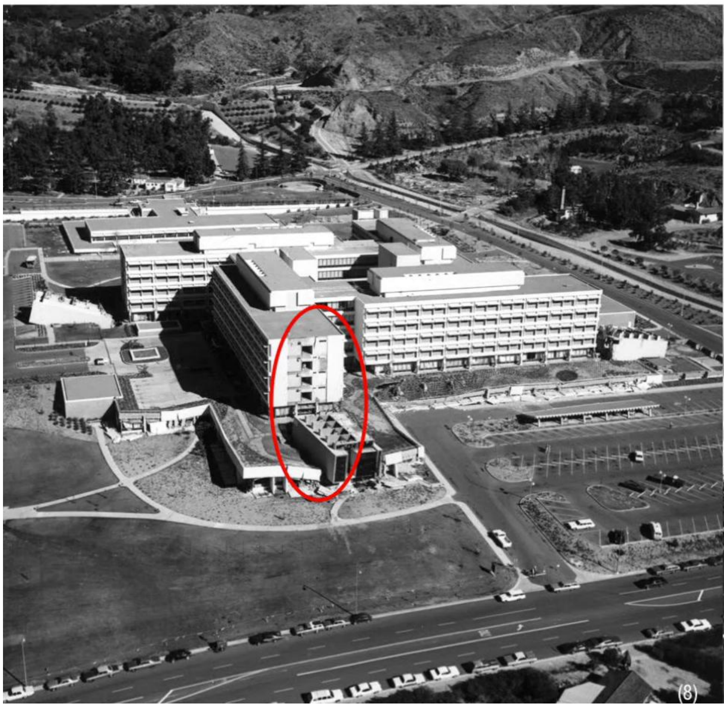


If one divides the building in two, one needs however, to provide a sufficiently large joint between the two buildings, so that the two buildings don't pound against each other during the earthquake. This applies, of course, also if you build just two completely independent buildings next to each other. There needs to be a sufficiently large gap in between, that they don't hit each other during an earthquake. Here on the right, you see a case where this rule was not respected.

Notes

Summary

4m 45s




An example of a building with a complex floor plan is the Olive View Hospital that was heavily damaged in the San Fernando earthquake in 1971. You can see here on the photo, that the building consists of four wings that are connected to each other, and this really creates a dynamic response that is really difficult to predict. But the building had another problem. Next to this complex floor plan, each wing was also made up of two structural systems. So the main part of the wing consisted of frames, and frames are rather flexible, but the end part of each wing was the staircase, and the staircase was built with relatively rigid walls. So these walls are really much more rigid than the frames, and therefore the frames during the earthquake were sort of leaning onto the walls, and they're transferring their forces to the walls. But the walls had not been designed for it and therefore these staircases failed, and in the end three of them actually fell over. Also the slabs that connected the frames to the walls had not been designed to transfer these forces and they broke too, as you can see here on the right, for the one staircase that actually remains standing up.

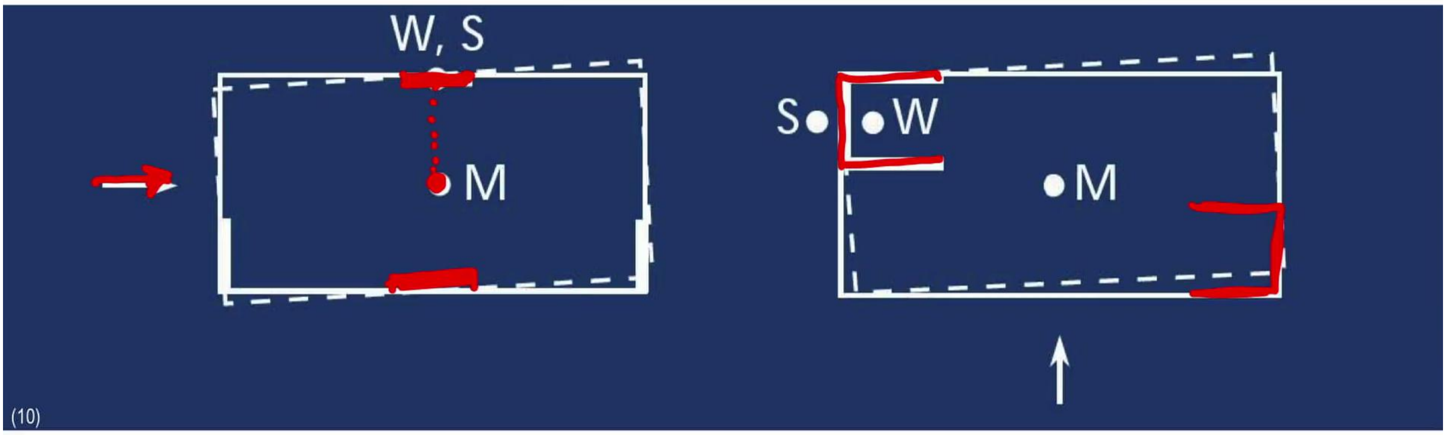
Notes

Summary

5m 14s

Conceptual seismic design

Avoid asymmetrical horizontal bracing



M = Center of mass (points where the resultant of inertia forces act)
W = Center of strength
S = Center of stiffness

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So if you combine two structural systems in one building, it is important to remember that you need to design the more stiffer structural element to take forces from the more flexible one, and you also need to design the slabs to transfer these forces. We should further make sure that the structural elements that provide the horizontal stiffness are well distributed over the floor plan. Here in this slide, you see two examples that are actually not so good. For example, if you look at the case on the left, if you consider an earthquake action from this direction, we only have this wall here that provides the horizontal stiffness and strength. So this wall is rather eccentric to the center of mass, which is at the center of the slab. So due to this eccentricity, the building will not only translate but it will also rotate. So the behavior of the building could really be improved if we added another wall here on the other side. The same applies to the building on the right. So here we have a core wall, which is often used to accommodate staircases and lift shafts, but again this wall is very eccentric with regard to the center of the mass. And the behavior of the building could really be improved if we added, for example, another core wall, or also just a simple wall on the other side of the building.

Notes

Summary

6m 30s

Conceptual seismic design

An example of a building that has an asymmetric floor layout is the O'Higgins Building in Concepcion that was damaged during the 2010 Chile earthquake. At the back of the building there's a long stiff wall. On the other three sides we have many windows, and hence these sides are much more flexible than the backside of the wall, and this can introduce some rotation to the building.

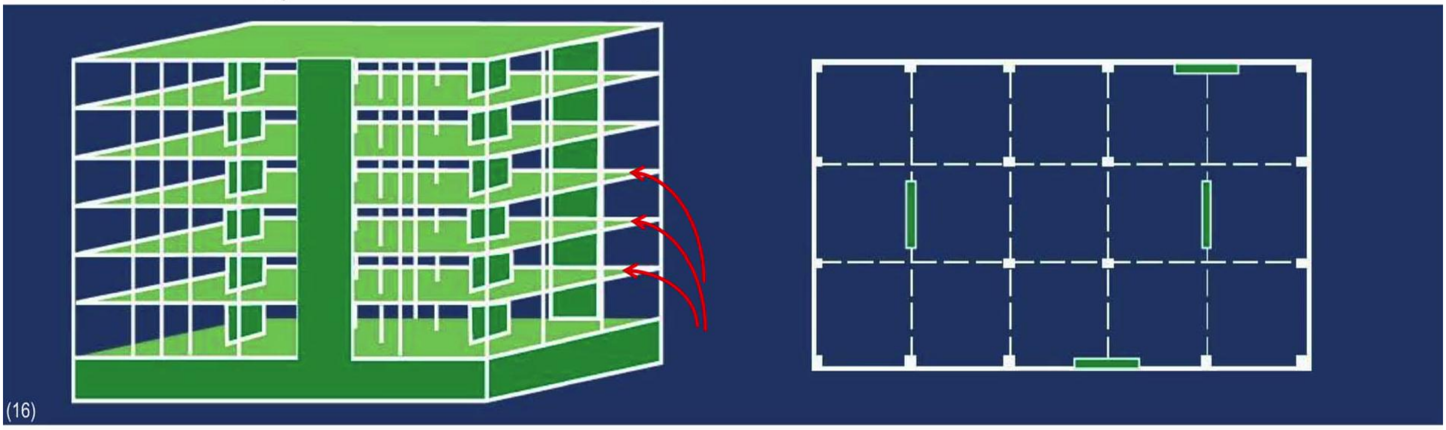
Notes

Summary

8m 05s

Conceptual seismic design

Choose floor systems that are stiff in-plane



Design floors with in-plane strength and stiffness
→ important for the distribution of inertia forces to the structural walls

So if you use walls to brace a building it's good to have at least two walls in each horizontal direction. The structural engineer can design these walls in such a way that they behave in a ductile manner. This means that they have a large deformation capacity. The deformation capacity is really a key to a robust structural performance, so it's really a very important point. If we place these walls at the perimeter of the building, we also obtain the torsional stiffness that we need. Walls are also good to control the deformations of one story. This will limit actually the damage to some of the non-structural elements. We will talk about this later. One part of the building that we actually not see normally, but which is very important for the seismic behavior, is the foundation. We need it to transfer the forces that are created as inertia forces in the upper part of the building to the ground. So a stiff foundation ensures a good force transfer to the ground, and it also prevents differential settlements between the walls and therefore limits the damage to the building. Another element of the building that is very important are the floors, the floor slabs.

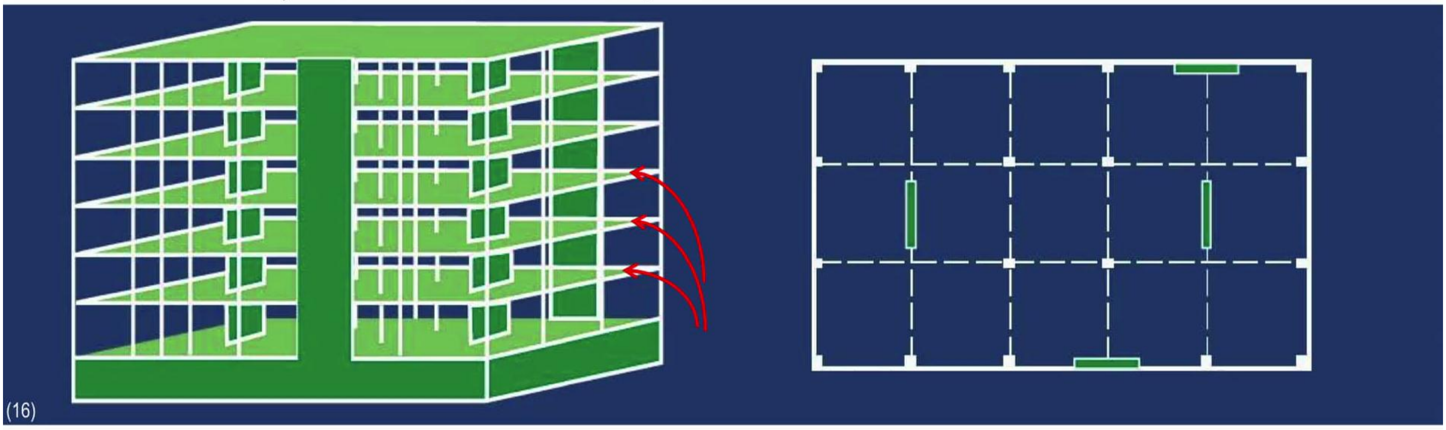
Notes

Summary

8m 30s

Conceptual seismic design

Choose floor systems that are stiff in-plane


(16)

Design floors with in-plane strength and stiffness
→ important for the distribution of inertia forces to the structural walls

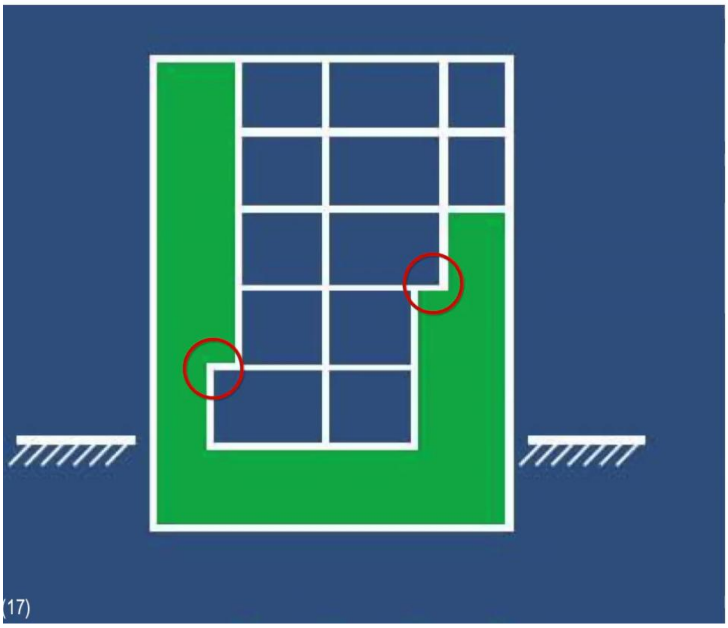
There we should really choose systems that are relatively stiff in-plane. This will allow us to transfer the forces from the floors back to the walls, and the walls can then take the forces down to the foundation. So if the floors are stiff in-plane, it will allow us to distribute the forces well between the different walls.

Notes

Summary

9m 51s

Vertical discontinuities in stiffness and strength cause problems



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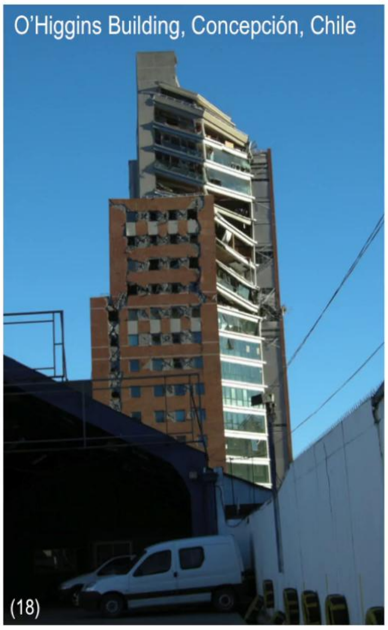


(18)

So let's go back to the vertical elements to the walls. In order to obtain a stable dynamic response, we should avoid discontinuities in these elements over the height of the building. In particular, reinforced concrete elements don't like discontinuities. Such setbacks will always cause stress concentrations and therefore concentrations of damage. The force demand increases from the top to the bottom in the element. It is therefore worse when the section is reduced, like here, than if it's increased, like here. An example of a building with irregularities in the elevation is, again, the O'Higgins Building that we've seen before. This building has really several setbacks over the height of the building, and that might have really contributed to the damage.

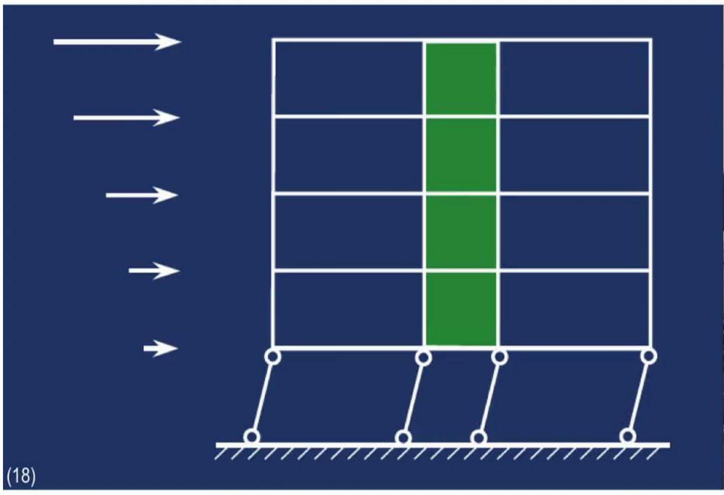
Notes

Summary

10m 18s

Conceptual seismic design

Avoid soft story mechanisms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One of the most common causes for the collapse of buildings during earthquakes is the soft story mechanism. Often the ground floor of a building is used for shops or parking spaces, and for these uses we need large open floor areas. The top floors, on the other hand, they're often used for offices or apartments, and we need walls to separate the rooms. As a result, we obtain a rather rigid box of the top floors that sits on this really flexible ground floor. So when the building is now subjected to an earthquake, all the deformations will concentrate in this flexible ground floor, and the deformation demands will soon be too big for the story and the story will collapse.

Notes

Summary

11m 11s

Conceptual seismic design

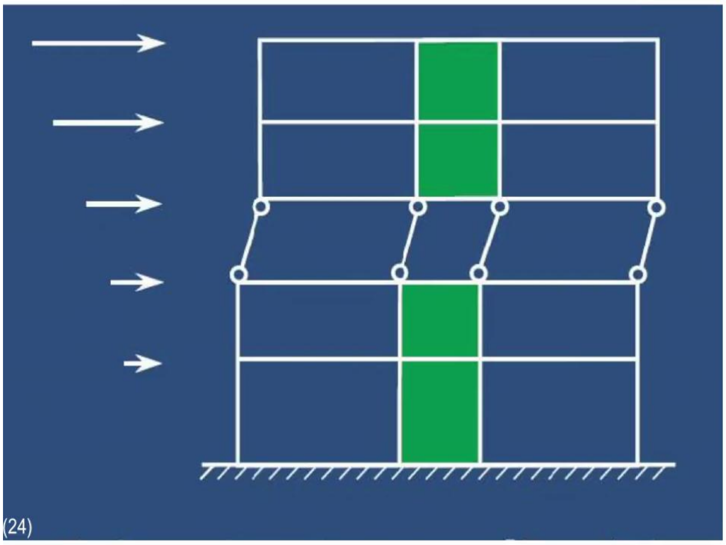
Here we have some examples of residential buildings that were damaged during the 2009 L'Aquila earthquake in Italy. These buildings have garages for cars on the ground floor, and apartments on the top floor. The large garage stores, the ground floors, was much softer than the top floors, and the deformations concentrated really in this ground floor. And for a number of these buildings this lead to the collapse of the ground floor. You see here on the right, the collapse of the ground floor, the columns are completely crushed, and the cars are sandwiched between two slabs. Fortunately, the earthquake happened during the night, and no one was in the garage and no one was harmed.

Notes

Summary

11m 58s

Avoid soft story mechanisms


(24)

(25)

Such soft stories are most common on the ground floor, but they can also form on upper floors. In the O'Higgins Building, one of the upper stories partially collapsed, most likely due to the discontinuity of some of the walls.

Notes

Summary

12m 43s

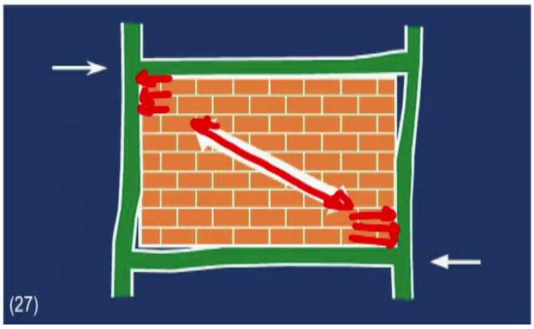
Reinforced concrete wall buildings


(26)

RC frames:

- Often in combination with masonry infills

Interaction of masonry infill with RC frame:


(27)

Let's now look a little bit more in detail at the other structural system and frames that we mentioned before. So reinforced concrete frames are often filled with masonry. One calls this masonry, *infills*. And the interaction of frames and infills is really rather complex. So you can see here, on the left, an example of a building that has, again, been damaged during the L'Aquila earthquake, and you can see that the cladding has fallen off, and actually also part of the masonry infills have fallen out. So these infills consisted here of two layers of masonry, and the outer layer has fallen out. Frames, as such, are rather flexible. The masonry infill, however, is rather stiff. The frame's the primary structural system and carries most of the horizontal loads. But when it tries to deform under an earthquake, a diagonal-- it sort of pushes against the masonry infill and a diagonal compression strut develops in the infill, and prevents part of the deformation of the frame. This can have two effects.

Notes

Summary

13m 00s

Reinforced concrete wall buildings

Typical failure modes

- In-plane interaction of masonry infills and RC frame

  → Can damage the frame

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For one, this force in the diagonal compression strut can become rather large, and then it pushes against the reinforced concrete frame, it can damage this frame, and in particular, the joint. You can see an example of such a damage, here on the left.

Notes

Summary

14m 08s

Reinforced concrete frames with masonry infills

(29)

Typical failure modes

- In-plane interaction of masonry infills and RC frame
  - → Can damage the frame
- Out-of-plane failure of masonry infills
  - → Repair costs
  - → Danger to people
  - → Can cause a soft-story mechanism or amplify the rotation

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Further, this force can also damage the masonry infill itself and lead to typical diagonal shear cracks. If an infill is cracked in shear, it becomes very vulnerable to out-of-plane accelerations. These are the accelerations that act perpendicular to the plane of the infill. If the infill is cracked, then only small out-of-plane accelerations are often sufficient to make the infill fail out of plane. This causes, of course, first of all, repair costs, but more importantly, the falling infill is also dangerous to people outside the building. And there's another point to consider. The failure of infills can also increase the likelihood of a soft story mechanism, and it might amplify torsion.

Notes

Summary

14m 25s

Reinforced concrete frames with masonry infills

Let's look again, at these buildings in L'Aquila. In this building on the top left, the infills did just not fall out, though you can clearly see that they were damaged, and they separated from the frame. So once the first infill really fails, the infills of the ground floor were those that were damaged most because the ground floor was already more flexible than the top floors due to the garage openings. So now if the infills of the ground floor fail, the ground floor will become even more softer, and this will really trigger, in the end, the soft story failure.

Notes

Summary

15m 15s

Reinforced concrete frames with masonry infills

Avoid partially infilled frames

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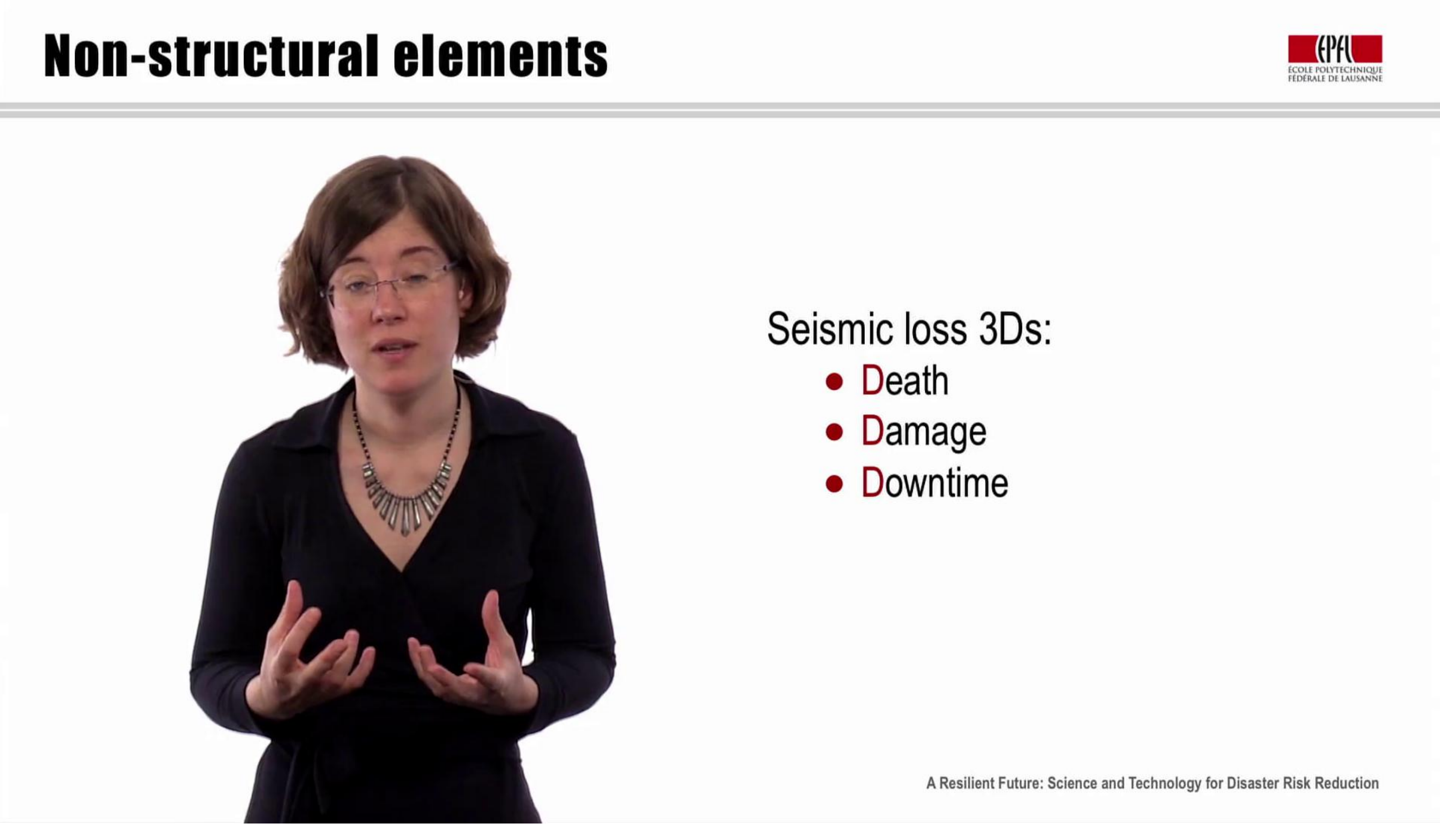
Sometimes the masonry infill do not reach over the entire height of the story, but part of the story is left free for window openings. One calls this a *partial infill*. These infills are particularly dangerous because they create short columns. These short columns are subjected to very high shear forces because most of the deformations in the columns really concentrate in the free part of the column.

Notes

Summary

15m 54s



So far we have talked about how earthquakes can damage structural systems. But the financial loss due to an earthquake has more components to it. We call these the *3Ds:* Death, Damage, and Downtime. The downtime is the loss caused when businesses are out of operation after an earthquake. Our primary goal of seismic engineering is, of course, to minimize the number of deaths, and the number of casualties, and injured people after an earthquake. But minimizing damage and downtime is also important.

Notes

Summary

16m 22s

Non-structural elements

Possible consequences of damage to non-structural components:

- Danger to people (falling pieces)
- Emission of dangerous substances (damage to piping, storage tanks)
- Fire
- Indirect effects (ex.: blocked emergency exits)
- Costs

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And when we talk of damage, we have so far considered the damage to the structural components but also the damage to non-structural components can be very important. So the non-structural components are all these components that are not contributing to the load transfer in a building, and also the content of a building. In some types of buildings, like for example hospitals, the costs caused by the damage to these components can be much larger than the costs caused to the damage to the structural components. So now we will look at some of the typical non-structural components, and how they can be damaged. Here we see some examples of non-structural components that failed. On the left, a partition wall that fell over, in the middle, suspended ceilings that fell down, and on the right, facade elements that fell down. And it can have secondary effects, like blocked emergency exits, it can cause fires, or the emission of dangerous substances.

Notes

Summary

17m 03s

Main points

- Aim for a robust behavior
- Conceptual seismic design requires cooperation between architect and engineer
- Earthquakes do not kill people, structures do
- Challenge lies with existing structures

So this was a brief overview on some fundamental aspects of the conceptual seismic design of buildings. To implement these effectively, it is really essential that architect and engineer work closely together right from the start of the project. We have also seen that we should not stop with the design of the structural system, but that we also need to consider the non-structural components. Their failure can be very dangerous and costly too. If you consider these guidelines, we can achieve that buildings are safe during earthquakes. The problem today lies really with existing buildings that have been constructed without considering these guidelines. Many of the most vulnerable buildings, such as buildings from past centuries, are part of our cultural heritage. The question how we can retrofit these without destroying their characteristic features is a current research topic.

Notes

Summary

18m 12s

References

- Bachmann, H. (2003) «Seismic conceptual design of buildings – basic principles for engineers, architects, building owners and authorities», Federal Office for Water and Geology, Bern, Switzerland.

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Notes

Summary

19m 05s

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Summary

19m 12s

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Notes

Summary

19m 15s