So we got to experiment a little bit with lateral force-resisting systems. The goal was to try to figure out pros and cons of different systems and specifically, to look at their stiffness. So which of them was stiffer? Which deflected less as you try to push on them?

The three main kinds, again, are a braced frame, a shear wall, and a moment-resisting frame. So every building really needs to have some type of one of those three systems. And sometimes they have multiple of those systems. And we're looking at how stiff-- how they're going to resist those applied loads, whether they come from earthquakes or from wind.

So you probably found that brace frame was pretty stiff. So using that truss system tends to be very stiff, also very efficient. Shear walls can also be very stiff but they tend to use more material, so there's pros and cons there.

From our single degree of freedom system experiments, when we experiment with the single degree of freedom model, we found that stiffer isn't always better-- that there's pros and cons. Sometimes we need the stiffness. When we get buildings that are really tall, if they're not stiff enough, there's too much motion. There are certain buildings in the world that you get too much motion at the top in a big wind and that's not comfortable.

And if your beams are not stiff enough, they deflect too much. So we have to balance how much is enough stiffness versus not enough. So why would we choose a brace frame versus a share well or a moment-resisting frame? Stiffness is one piece of the puzzle but there's other reasons. So a moment-resisting frame tends to be the choice for a lot of buildings because it allows, at least on the exterior, allows windows. So we have a lot more open space for windows. It is one of the least stiff options but it provides other things that are useful.

Shear walls are the opposite. No options for windows in a shear wall but we often use them in the core of a building. So around elevators and staircases, we'll put shear walls. And they're very stiff, and so they'll help us stiffen up the interior of the building.

But engineering is all about all these competing criteria, so it's not just stiffness. It's also strength. But it's aesthetics and functionality. And cost is a big factor. So how you pick different systems will depend on all those criteria.

So I want talk a little bit about how structures-- so putting all these pieces together-- how it's changed over history. So we've talked a little bit about the early structures and stone. We talked about beams. We talked about stone.

Stone was used in many of the early structures. Stone is very strong in compression so it does a great job with arches and vaults and domes. It is very weak in tension. People did use them for beams and they used them for buildings but the spans of the beams tended to be very small, very short. Again, because it doesn't have very much tension capacity and those beams rely on both tension and compression.

So if you look at a plan view of ancient buildings-- so examples would be the Parthenon, Temple of Zeus, any of the large stone structures. If you look at a plan view, you'll see lots of columns very closely spaced throughout the building. That's because stone, if it's used for the beams, cannot span very far. It could span a little bit farther when they started using arches, so in many of the cathedrals, they would use arches and vaults. And so the spans got a little greater, heights got a little higher. But still, you were limited by your material.

It wasn't until the 1700s, with the advent of steel and iron, that we started to be able to span further. So columns would be able to be spaced further apart. So we started to get more open space. We started to get taller buildings.

So one of the first examples of a steel moment-resisting frame-- moment-resisting frames were the most common system used in early buildings-- was the Wainwright Building in Saint Louis. So there were a lot of big buildings going up in Saint Louis. If you remove the outer skin of the building, you'll see steel columns and beams. It was designed by Louis Sullivan and think Dankmar Adler. They went on to design many buildings together.

That was one of the first moment-resisting frames. There was around that time-- around the 1900s-- an unofficial skyscraper competition began. It was mainly New York and Chicago competing, trying to get the tallest structure.

So the Woolworth Building is an example of that. It was commissioned by Franklin Woolworth. The entire goal was to build the tallest building. So Franklin Woolworth paid $13.5 million in cash for the building.

It was completed in 1913. It was 241 meters tall. And it was the tallest until 1930. It was designed by engineers Gunvald Aus and Kort Berle.

Again, like many of the early buildings, it used a steel moment-resisting frame. The was again to get a lot of windows. That was one of the first systems that was used. It also was the first building that would include an elevator, which is the key to making buildings go taller. So if you want to get buildings taller, we started to have to think about fires and getting people in and out.

The next building-- completed in 1931-- that I want to talk about, because it took over as the tallest, is the Empire State Building. It was completed in 1931. It was the tallest until 1972. It was designed by William Lamb and Homer Balcom.

One of the keys about this building is the speed with which was built. It was designed and built in 20 months. So it was when people are starting to use an assembly line approach and construction was also using an assembly line approach. It's an iconic building. It was designed in art deco style so many people recognize it. It's often referred to as the most famous skyscraper in the world.

Internally, it's using a steel moment-resisting frame, again, to resist those lateral loads. But it was the tallest for many, many years.

Next building I want to talk about is the John Hancock tower. And this never was actually the tallest in the world, but it introduced a new type of framing for structures that actually helped structures in general become taller. So it introduced a tubed structure.

So up until then, buildings were traditionally very regular. So all the columns were space regularly. The John Hancock tower uses a trussed tube, so if you look at the exterior you'll see X's on the outside. And that's a truss on the outside or a tube structure.

It was designed by engineer Fazlur Khan with the help of architect Bruce Graham. They both work for Skidmore Owings and Merrill. Fazlur Khan-- he's a famous engineer. He's known as the father of the tube structure. He's a Bangladeshi American engineer and he introduced the tube. He is the one that invented and started using a tube structure.

So instead of that traditional grid of columns placed very regularly throughout the building, he moved everything to the outside of the building-- not everything, but most the columns and the lateral force-resisting system was moved to the outside. This turned out to be much more efficient and economical. It has to do with the stiffness.

So if we go back and think about beams-- beams that have all the mass concentrated right at the center were not nearly as stiff as beams that had the mass further away. That's why we use I-beams. That's why we go to forms that have everything moved away from that central axis. It was the same with buildings. So we're moving the columns and the lateral force-resisting system to the outside-- it was more efficient.

Fazlur Khan also designed the Willis Tower-- formerly known as the Sears Tower. It's again a tubed frame system, not with a truss, but still tubed frame, so everything on the outside. It was completed in 1973 and it was the tallest for almost 25 years.

So the Burj Khalifa in Dubai is currently the tallest building in the world. It's got a height of almost 830 meters, which is huge. It's three times the height of the Eiffel Tower, to give you perspective. Another way to give you perspective is the way the concrete that was used. The weight of the concrete in the building is equal to the weight of 100,000 elephants.

Another statistic that I found interesting was that 12,000 people worked on the Burj Khalifa during the peak of construction. The Burj Khalifa was designed by engineer Bill Baker and architect Adrian Smith. They're both at Skidmore Owings and Merrill.

It's interesting to read about this design. It's based on a flower. It also uses a bundled tube construction. But it's got these three arms, so it's got a very strong core. And then as it goes up, less and less it tapers, somewhat like the Willis Tower.

The reason it has these three arms is so it can resist wind in any direction. So it has these three arms-- it gives them a nice moment of inertia at the base. So you have a strong core and then these arms that extend out to give it some stiffness. So as tries to bend, it's got stiffness in any direction.

That goes back, again, to beam theory and moment of inertia. There was extensive wind tunnel testing that was done on models of the Burj Khalifa and also detailed computer analyses. It's just an amazing feat and it brings all of our systems together.

So we have another video coming up on using glass as a structural material. Go ahead and check that out. And then a couple final activities for the course.