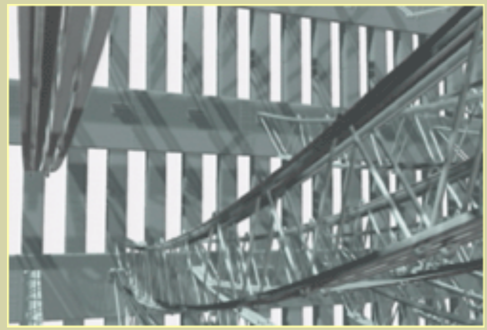
The Collapse: An Engineer's Perspective



Animation of a floor truss in the World Trade Center giving way.

It wasn't until Dr. Thomas Eagar saw Building 7 of the World Trade Center implode late on the afternoon of September 11th that he understood what had transpired structurally earlier that day as the Twin Towers disintegrated. A professor of materials engineering and engineering systems at the Massachusetts Institute of Technology, Eagar went on to write an influential paper in the journal of the Minerals, Metals, and Materials Society entitled "Why Did the World Trade Center Collapse? Science, Engineering, and Speculation" (*JOM,* December 2001). In this interview, Eagar explains the structural failure, what can be done within existing skyscrapers to improve safety, and what he believes the most likely terrorist targets of the future may be.

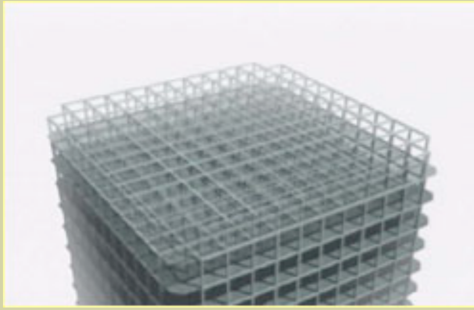
NOVA: After the planes struck and you saw those raging fires, did you think the towers would collapse?

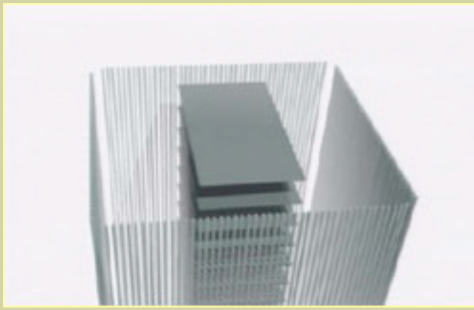
Eagar: No. In fact, I was surprised. So were most structural engineers. The only people I know who weren't surprised were a few people who've designed high-rise buildings.

NOVA: But you weren't surprised that they withstood the initial impacts, is that correct?

Eagar: That's right. All buildings and most bridges have what we call redundant design. If one component breaks, the whole thing will not come crashing down. I once worked on a high-rise in New York, for example, that had a nine-foot-high beam that had a crack all the way through one of the main beams in the basement. This was along the approach to the George Washington Bridge. They shored it up and kept traffic from using that area.

Some people were concerned the building would fall down. The structural engineers knew it wouldn't, because the whole thing had an egg-crate-like construction. Or you can think of it as a net. If you lose one string on a net, yes, the net is weakened but the rest of the net still works.





Earlier skyscrapers (top) had columns spaced evenly across every floor. The World Trade Center (bottom) broke with tradition by having columns only in the central core and along the exterior walls.

That's essentially how the World Trade Center absorbed an airplane coming into it. It was somewhat like the way a net absorbs a baseball being thrown against it. If you lose a couple of the columns, that's not the end of the world. It will still stand up.

NOVA: The World Trade Center was also designed to take a major wind load hitting from the side.

Eagar: Yes. A skyscraper is a long, thin, vertical structure, but if you turned it sideways, it would be like a diving board, and you could bend it on the end. The wind load is trying to bend it like a diving board. It sways back and forth. If you've been on the top of the Sears Tower in Chicago or the Empire State Building on a windy day, you can actually feel it. When I was a student, I visited the observation deck of the Sears Tower, and I went into the restroom there, and I could see the water sloshing in the toilet bowl, because the wind load was causing the whole building to wave in the breeze.

NOVA: Are skyscrapers designed that way, to be a little flexible?

Eagar: Absolutely. Now, there are different ways to design things. For example, Boeing designs their aircraft wings to flap in the breeze, while McDonnell Douglas used to design a very rigid wing that would not flex as much. You can design it both ways. There are trade-offs, and there are advantages to both ways.

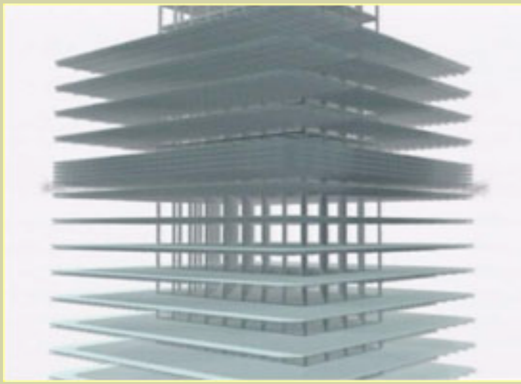
"Most buildings are designed to sway in the breeze."

Most buildings are designed to sway in the breeze. In fact, one of the big concerns in the early design of the World Trade Center, since it was going to be the tallest building in the world at the time, was that it not sway too much and make people sick. You can get seasick in one of these tall buildings from the wind loads. So they had to do some things to make them stiff enough that people wouldn't get sick, but not so rigid that it could snap if it got too big a load. If something's flexible, it can give; think of a willow tree. If you have a strong wind, you want the building, like the tree, to bend rather than break.

NOVA: Brian Clark, one of only four people to get out from above

where United 175 hit the South Tower, says that when the plane struck, the building swayed for a full seven to 10 seconds in one direction before settling back, and he thought it was going over.

Eagar: That estimate of seven to ten seconds is probably correct, because often big buildings are designed to be stiff enough that the period to go one way and back the other way is 15 or 20 seconds, or even 30 seconds. That keeps people from getting sick.



Upper floors pancaked down onto lower floors, causing a domino effect that left each building in ruins within ten seconds.

NOVA: The Twin Towers collapsed essentially straight down. Was there any chance they could have tipped over?

Eagar: It's really not possible in this case. In our normal experience, we deal with small things, say, a glass of water, that might tip over, and we don't realize how far something has to tip proportional to its base. The base of the World Trade Center was 208 feet on a side, and that means it would have had to have tipped at least 100 feet to one side in order to move its center of gravity from the center of the building out beyond its base. That would have been a tremendous amount of bending. In a building that is mostly air, as the World Trade Center was, there would have been buckling columns, and it would have come straight down before it ever tipped over.

Have you ever seen the demolition of buildings? They blow them up, and they implode. Well, I once asked demolition experts, "How do you get it to implode and not fall outward?" They said, "Oh, it's really how you time and place the explosives." I always accepted that answer, until the World Trade Center, when I thought about it myself. And that's not the correct answer. The correct answer is, there's no other way for them to go but down. They're too big. With anything that massive -- each of the World Trade Center towers weighed half a million tons -- there's nothing that can exert a big enough force to push it sideways.

NOVA: I think some people were surprised when they saw this massive 110-story building collapse into a rubble pile only a few stories tall.

Even traveling at hundreds of miles an hour, the planes that struck the World Trade Center did not have enough force to knock the towers over.

Eagar: Well, like most buildings, the World Trade Center was mostly air. It looked like a huge building if you walked inside, but it was just like this room we're in. The walls are a very small

fraction of the total room. The World Trade Center collapse proved that with a 110-story building, if 95 percent of it's air, as was the case here, you're only going to have about five stories of rubble at the bottom after it falls.

NOVA: You've said that the fire is the most misunderstood part of the World Trade Center collapse. Why?

Eagar: The problem is that most people, even some engineers, talk about temperature and heat as if they're identical. In fact, scientifically, they're only related to each other. Temperature tells me the intensity of the heat -- is it 100 degrees, 200 degrees, 300 degrees? The heat tells me how big the thing is that gets hot. I mean, I could boil a cup of water to make a cup of tea, or I could boil ten gallons of water to cook a bunch of lobsters. So it takes a lot more energy to cook the lobsters -- heat is related to energy. That's the difference: We call the *intensity* of heat the temperature, and the *amount* of heat the energy.

Continue: The heat was much greater than might have been expected in a typical fire?

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NOVA: So with the World Trade Center fire, the heat was much greater than might have been expected in a typical fire?

Watch an animation of the Boeing 767 aircraft hitting the North Tower and the rapid spread of the resulting fireball through the building.

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Eagar: Right. We had all this extra fuel from the aircraft. Now, there have been fires in skyscrapers before. The Hotel Meridien in Philadelphia had a fire, but it didn't do this kind of damage. The real damage in the World Trade Center resulted from the *size* of the fire. Each floor was about an acre, and the fire covered the whole floor within a few seconds. Ordinarily, it would take a lot longer. If, say, I have an acre of property, and I start a brushfire in one corner, it might take an hour, even with a good wind, to go from one corner and start burning the other corner.

That's what the designers of the World Trade Center were designing for—a fire that starts in a wastepaper basket, for instance. By the time it gets to the far corner of the building, it has already burned up all the fuel that was back at the point of origin. So the beams where it started have already started to cool down and regain their strength before you start to weaken the ones on the other side.

On September 11th, the whole floor was damaged all at once, and that's really the cause of the World Trade Center collapse. There was so much fuel spread so quickly that the entire floor got weakened all at once, whereas in a normal fire, people should not think that if there's a fire in a high-rise building that the building will come crashing down. This was a very unusual situation, in which someone dumped 10,000 gallons of jet fuel in an instant.

NOVA: How high did the temperatures get, and what did that do to the steel columns?

Eagar: The maximum temperature would have been 1,600°F or 1,700°F. It's impossible to generate temperatures much above that in most cases with just normal fuel, in pure air. In fact, I think the World Trade Center fire was probably only 1,200°F or 1,300°F.

Investigations of fires in other buildings with steel have shown that fires don't usually even melt the aluminum, which melts around 1,200°F. Most fires don't get above 900°F to 1,100°F. The World Trade Center fire did melt some of the aluminum in the aircraft and hence it probably got to 1,300°F or 1,400°F. But that's all it would have taken to trigger the collapse, according to my analysis.

NOVA: You've pointed out that structural steel loses about half its strength at 1,200°F, yet even a 50 percent loss of strength is insufficient, by itself, to explain the collapse.

Eagar: Well, normally the biggest load on this building was the wind load, trying to push it sideways and make it vibrate like a flag in the breeze. The World Trade Center building was designed to withstand a hurricane of about 140 miles an hour, but September 11th wasn't a windy day, so the major loads it was designed for were not on it at the time.

"You can't explain the collapse just in terms of temperature."

As a result, the World Trade Center, at the time each airplane hit it, was only loaded to about 20 percent of its capacity. That means it had to lose five times its capacity either due to temperature or buckling—the temperature weakening the steel, the buckling changing the strength of a member because it's bent rather than straight. You can't explain the collapse just in terms of temperature, and you can't explain it just in terms of buckling. It was a combination.

NOVA: So can you give a sequence of events that likely took place in the structural failure?

Eagar: Well, first you had the impact of the plane, of course, and then this spreading of the fireball all the way across within seconds. Then you had a hot fire, but it wasn't an absolutely uniform fire everywhere. You had a wind blowing, so the smoke was going one way more than another way, which means the heat was going one way more than another way. That caused some of the beams to distort, even at fairly low temperatures. You can permanently distort the beams with a temperature difference of only about 300°F.

NOVA: You mean one part of a beam is 300°F hotter than another part of the same beam?

Eagar: Exactly. If there was one part of the building in which a beam had a temperature difference of 300°F, then that beam would have become permanently distorted at relatively low temperatures. So instead of being nice and straight, it had a gentle curve. If you press down on a soda straw, you know that if it's perfectly straight, it will support a lot more load than if you start to put a little sideways bend in it. That's what happened in terms of the beams. They were weakened because they were bent by the fire.

But the steel still had plenty of strength, until it reached temperatures of 1,100°F to 1,300°F. In this range, the steel started losing a lot of strength, and the bending became greater. Eventually the steel lost 80

percent of its strength, because of this fire that consumed the whole floor.

If it had only occurred in one little corner, such as a trashcan caught on fire, you might have had to repair that corner, but the whole building wouldn't have come crashing down. The problem was, it was such a widely distributed fire, and then you got this domino effect. Once you started to get angle clips to fail in one area, it put extra load on other angle clips, and then it unzipped around the building on that floor in a matter of seconds.

NOVA: Many other engineers also feel the weak link was these angle clips, which held the floor trusses between the inner core of columns and the exterior columns. Is that simply because they were much smaller pieces of steel?

Watch an animation of the floor trusses giving way, followed by the buckling of the outer columns.

QuickTime | RealVideo: 56K/ ISDN+

Eagar: Exactly. That's the easiest way to look at it. If you look at the whole structure, they are the smallest piece of steel. As everything begins to distort, the smallest piece is going to become the weak link in the chain. They were plenty strong for holding up one truss, but when you lost several trusses, the trusses adjacent to those had to hold two or three times what they were expected to hold.

Those angle clips probably had two or three or four times the strength that they originally needed. They didn't have the same factor-of-five safety as the columns did, but they still had plenty of safety factor to have people and equipment on those floors. It was not that the angle clips were inadequately designed; it was just that there were so many of them that the engineers were able to design them with less safety factor. In a very unusual loading situation like this, they became the weak link.

NOVA: I've read that the collapse was a near free-fall.

Eagar: Yes. That's because the forces, it's been estimated, were anywhere from 10 to 100 times greater than an individual floor could support. First of all, you had 10 or 20 floors above that came crashing down. That's about 10 or 20 times the weight you'd ever expect on one angle clip. There's also the impact force, that is, if something hits very hard, there's a bigger force than if you lower it down very gently.

NOVA: Miraculously, a number of firefighters survived inside Tower One. They were on the third or fourth floor in a stairwell, and immediately after the collapse they looked up and saw blue sky above their heads—their part of the stairwell survived. How is that possible, with all the force of that 500,000-ton building coming down?

Eagar: Well, you have to

understand the stairwells were reinforced areas of the building. The stairwells were in the central core, which had more steel than the outer areas, which were big open floors. So that extra steel formed a little cage to protect them. It's still amazing, though.

Now, there could have been someone two floors below who could have been completely crushed. It just depends on how the steel buckled. If you take that soda straw again, and you push it sideways, it will develop a buckle at some location, probably somewhere in the middle third. Well, if you happen to be where the buckling occurs, that area is going to get smashed, but if you're, say, below where the buckling occurred, basically the whole thing can push sideways. They were very, very fortunate that they happened to be in an area that was somewhat shielded and protected by all the extra steel in the central core.

I read one of those people's statements in the paper the other day, and he said that if they'd been in the lobby, they'd be gone. I was in the lobby of the World Trade Center years ago, and it was some three or four stories tall. What was going to buckle? Well, the lobby had the longest columns, so they were going to buckle. Those firefighters were just above that, so they were protected by the buckling underneath, within this sort of steel cage.

In fact, that's how they design automobiles for crashworthiness. They try to design the passenger compartment to be a cage, and the hood and trunk are supposed to deform and absorb the energy so that you're protected by this little cage of steel that hopefully won't deform.

NOVA: There's a theory that the aluminum of the planes caught fire.

Engineers have found evidence that the aluminum of the planes' fuselages and wings may have melted, but there is no evidence that it burned.

Eagar: Yes, a number of people have tried to reinforce that theory. Now, the aluminum of the planes would have burned just like a flare. Flares are made out of aluminum and magnesium, so are fireworks, and they burn hot enough to melt steel in certain cases.

However, they have had people sorting through the steel from the World Trade Center, and no one has reported finding melted steel, which means that we didn't have that aluminum flare. In any case, burning aluminum would have been white-hot, about 4,000°F, and someone would have seen it even through that dense black smoke.

Of course, aluminum can burn. That's what demolished the [British destroyer] *Sheffield* in the Falklands War [when it was struck by an Argentinian missile]. It wasn't the Exocet missile that destroyed the superstructure of the *Sheffield*. The missile wasn't big enough, just like the plane wasn't big enough to bring down the World Trade Center. That Exocet missile did damage the *Sheffield,* but what doomed the *Sheffield*

was the aluminum superstructure caught fire and burned. So you suddenly had something like 1,000 or 10,000 times as much fuel as you had in that Exocet missile.

Now, this is *not* a type of fire we have to worry about in buildings. We don't have anywhere close to those types of conditions. And we didn't have those in the World Trade Center, in my opinion.

NOVA: How soon will a definitive report of the causes of the collapse be released?

Eagar: Well, there's some very sophisticated analysis that various people in the government, at universities, and at structural engineering firms are doing to understand it. Most of those people have not yet published any conclusions. To do a good job of research on something like this can typically take one to two years. I don't expect to see any conclusive reports probably until about the first anniversary of the attack.

"There will still be people worrying about this ten years from now."

There are different levels of analysis. You can do the back-of-the-envelope, which was what I and other people did early on. But to do the full analysis will take much longer. I suspect there will still be people worrying about this ten years from now.

NOVA: In your back-of-the-envelope analysis, you concluded the World Trade Center was not defectively designed, but not everyone apparently accepts that conclusion.

Eagar: A lot of people said, Well, the building failed. That's true, but nothing is indestructible. The question is, why did it fail? In this case, as I've explained, it was the fire covering the whole floor in a few seconds that made this different from any other fire that anyone had ever designed for.

If people say, Well, couldn't we have designed it for this, I say, Yes, we could have. We could build buildings that could survive a jet running into them with a full fuel load. In fact, the military does. But they're bunkers. We build these things for the President and the rest of the 150 leaders of the country to go to as a secure area. You can do that, but your building costs go up by a factor of about 100. Well, do we want to have 100 times fewer homes for people to live in? Do we want to have 100 times fewer roads?

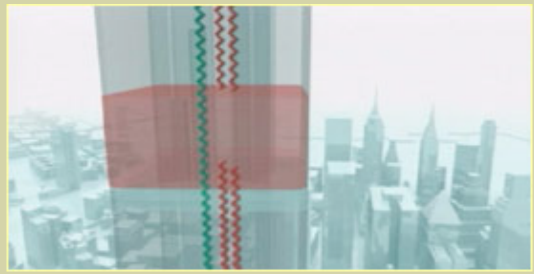
If we were to harden everything against a terrorist attack, we'd push ourselves back into the first half of the 19th century in terms of living style. Now, some people might consider that an improvement, but not everybody, so society has some important tradeoffs here. There's got to be some middle ground where we can make things more secure but not destroy our standard of living.

NOVA: Anything we should do now to retrofit existing skyscrapers like

the Sears Tower?

Eagar: Well, one of the things that's really important and is relatively inexpensive is a public communication system. I've been in high-rises when the fire alarm goes off, and everyone looks around the room and decides, Should we just continue meeting and ignore the fire alarm, or should we evacuate? Fortunately, in most cases—and I've had to be the person in a few of those cases—people say, Look, it's a fire alarm. We don't know if it's real. Evacuate. So you need better public-address systems to inform people that this is not a test, this is not a false alarm, you'd better get out of the building.

Survivors from the World Trade Center have said that some people took four or five minutes to figure out there was something more than just some false alarm. Other people started moving immediately. Obviously, the quicker people started to move, the better chance they had of reaching safety.



Better communications systems may have allowed more people to escape the towers before they collapsed, Eagar believes. For instance, if more people had known that Stairway A in the South Tower, shown here in green, had survived the impact, more people may have gotten out before the building collapsed.

NOVA: How about improving the fire safety of the building or putting in extra stairwells?

Eagar: These are very difficult things to redesign into current buildings. They can and will be added to future buildings. The simplest thing is the communication system. And better training of firefighters. Those things will definitely be done.

If you look at the World Trade Center disaster, it would have been greatly minimized if the safety personnel had been aware of the danger they were in. They didn't realize it was going to collapse. As I said earlier, there are only a few engineers in the country who had ever designed skyscrapers like this who would have realized, but they couldn't communicate within that first hour with the people at ground zero. Nobody could call to New York City at that time.

So better communication. The military's known that for years. They've invested tremendous amounts of money in better communications. That's been one of the differences in having fewer lives lost on the American side in recent wars. We've got much better C^3I—Command, Control, Communications, and Intelligence. They've spent billions of dollars, and it's saved thousands and thousands of lives in the military. We can do that on the civilian side as well for these big structures, though, in my opinion, skyscrapers are not the problem anymore.

"A terrorist is not going to attack the

NOVA: What is?

Eagar: I think the terrorist danger will be other things. A terrorist is not

things you expect him to attack."

going to attack the things you expect him to attack. The real problem is pipelines, electrical transmission, dams, nuclear plants, railroads. A terrorist's job is to scare people. He or she doesn't have to harm very many people. Anthrax is a perfect example. If someone could wipe out one electrical transmission line and cause a brownout in all of New York City or Los Angeles, there would be hysteria, if people realized it was a terrorist that did it.

Fortunately, we have enough redundancy—the same type of redundancy we talk about structurally in the World Trade Center—in our electrical distribution. We have that redundancy built in. I shouldn't say this, but this was how Enron was able to build up a business, because they could transfer their energy from wherever they were producing it into California, which was having problems, and make a fortune—for a short period of time.

NOVA: Gas pipelines don't have redundancy built in, though.

Eagar: No, but one advantage of a gas pipeline is the damage you can do to it is relatively limited. You might be able to destroy several hundred yards of it, but that's not wiping out a whole city. The bigger problem with taking out a gas pipeline is if you do it in the middle of winter, and that gas pipeline is heating 20 percent of the homes in the Northeast. Then all of a sudden you have 20 percent less fuel, and everybody's going to have to turn the thermostat down, and you're going to terrorize 30 million people.

The lesson we have to learn about this kind of terrorism is we have to design flexible and redundant systems, so that we're not completely dependent on any one thing, whether it's a single gas pipeline bringing heat to a particular area or whatever.

Remember the energy crisis in 1973? That terrorized people. People were sitting in long lines at gas pumps. It takes five or 10 years for society to readjust to a problem like that. What happened in the energy crisis in 1973 was we had essentially all our eggs in one basket—the oil basket. But by 1983, electric generating plants could flip a switch and change from oil to coal or gas, so no one could hold a gun to our head like they did before.

Thomas Eagar is Thomas Lord Professor of Materials Engineering and Engineering Systems at MIT. He was recently nominated to serve on a National Research Council committee on homeland security. To see Eagar's article, "Why Did the World Trade Center Collapse? Science, Engineering, and Speculation," which was coauthored by MIT graduate student Christopher Musso, go to www.tms.org/pubs/journals/JOM/0112/Eagar/Eagar-0112.html

Interview conducted by Peter Tyson, editor in chief of NOVA Online

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