WORLD TRADE CENTER

After the Fall

Researchers have found some, but not all, of the answers about why the twin towers of the World Trade Center collapsed—and why they stood for as long as they did. Did floor trusses or internal columns fail first?

NEW YORK CITY—Chief engineer Francis Lombardi was sitting in his New York Port Authority office on the 72nd floor of the North Tower of the World Trade Center at 8:48 a.m. on 11 September when he felt the building shudder. It must be an earthquake, he remembers thinking. But the smoke that began pouring from the floors above him—and the fireball that shot out of the South Tower 15 minutes later—soon made it clear that something worse, and more deadly, had struck both buildings. Two months later, scientists and engineers have gathered reams of data on what happened. But they still lack definite answers on why the 110-story towers collapsed almost vertically after standing long enough to allow more than 25,000 people to escape.

Clearing the air. Researchers are analyzing the plumes of smoke from the twin towers for clues about the intensity and nature of the fires within.

Meeting last week at a forum at Columbia University,* engineers agreed that the impact of the hijacked planes themselves probably would not have brought down either building without the intense heat from the fires that followed. "I was flabbergasted" when the towers fell, concedes Charles Thornton, chair of the Thornton-Tomasetti Group, the structural design firm for the world's tallest buildings, the Petronas Towers in Malaysia. Thornton and others investigating the collapses feel they are making progress toward pinning down the structural cause of the initial failure that led to the floor-by-floor pancaking and subsequent collapse of each entire building. They are far from reaching agreement, however. Determining what triggered the deadly cascade is "the $64,000 question," says Lombardi. "The answer is not yet clear to me."

Engineers and scientists are pursuing several lines of inquiry, from forensic analysis of the towers' twisted steel columns to computer modeling of the smoke plumes that followed the crashes. While the exact mechanism of the towers' collapse may never be proven, there are plenty of strong opinions. Some experts think that the first structural element to fail in the intense heat and pressure were the steel floor trusses—which spanned the distance between each tower's inner core of 47 columns and its perimeter columns (59 across each side of the towers). But other engineers suspect that some inner columns damaged by hurtling pieces of the aircraft failed when high temperatures weakened the steel. Several experts also say the loss of fireproofing—which was stripped off trusses or columns by the impact of chunks of the aircraft during the collisions—may have been an important factor. It may take months to resolve which of these processes, or perhaps a deadly combination of all of them, brought the buildings down.

Researchers are focusing in particular on the fires set off by the ignition of an estimated 75,000 liters of jet fuel splattered from each aircraft. The inferno may have exposed the columns and the floor supports to temperatures of 800 degrees C or higher, which would have further weakened the steel columns and support structures already damaged by the collisions. "Fire and fire protection is one of the most important issues we should examine as a result of this collapse," says Matthys Levy, a partner of the civil and structural engineering firm Weidlinger Associates Inc. and author of *Why Buildings Fall Down*.

Sifting for clues

W. Gene Corley, senior vice president of Construction Technology Laboratories in Skokie, Illinois, leads a team of 21 engineers assembled by the American Society of Civil Engineers (ASCE) shortly after the tragedy. The team hopes to issue a preliminary report next spring on the mechanism of the twin towers' collapse. Corley says some members are now trying to identify and analyze thousands of steel columns found in the rubble, a process aided by markers stamped on each one when the towers were erected showing their exact location in the building. Of particular interest are columns struck by the aircraft or contorted by the intense heat. But other experts are dubious about the lessons to be learned from that exercise, because some of the damage may have been caused by the fires smoldering underneath the rubble after the collapse. Forensic steel specialists have been identifying and analyzing such columns both at the site and at landfills where the rubble has been taken.

Taking another tack, some members of the ASCE team are analyzing numerous videos and detailed still photos of the towers between the time of the initial aircraft impacts and the collapses. "With the right photos, we can count every [exterior] column and determine whether it was damaged or destroyed by the crash itself," Corley says. "And we can analyze windows to see how many were broken, allowing us to estimate how much air was coming into the fires in the buildings." The computer modeling may help explain the way the fire burned and perhaps the approximate temperatures it reached, contributing to the separate collapses of the two towers.

Many investigating engineers believe that the South Tower—which was struck 15 minutes later than the North Tower but fell 29 minutes before its twin—collapsed more

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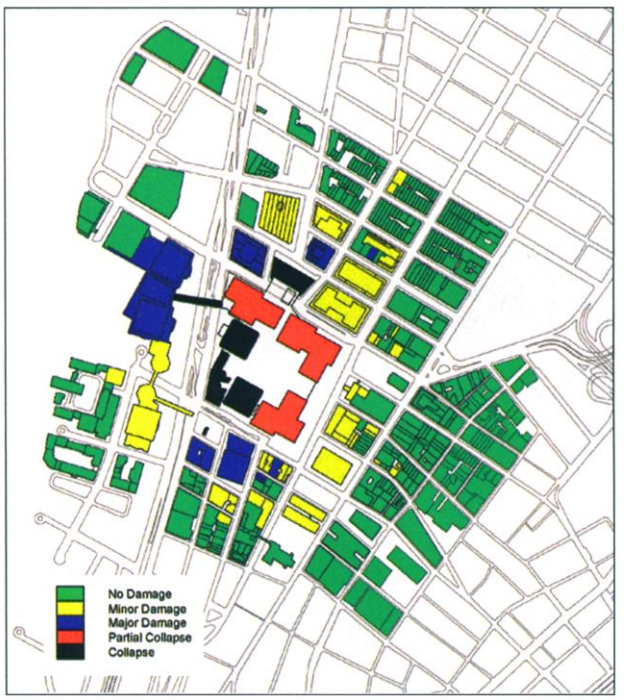
* "The Technical Implications of the World Trade Center Collapse," Columbia University, New York City, 12 November.

quickly because the two planes slammed into the buildings at different places. The second crashed off-center and likely damaged more of the interior columns. It also hit lower, meaning that the weakened columns had to support the weight of 15 more floors above them. The collapses of the twin towers also took down several other buildings in the complex (see map), a process that engineers hope will teach them lessons about collateral damage.

In fact, some engineers say that Buildings 5 and 7 may yield more valuable tips on safety than the twin towers themselves, because structures are far more likely to suffer damage from fires and projectiles than from an aircraft's collision itself. The 47-story Building 7, which collapsed in the evening after burning all day, offers investigators an unusual example of a protected steel structure brought down by a fire. The unusual projectile damage to Building 5 is also drawing scrutiny.

The revelation that an intense fire could destroy a damaged steel-girdered structure has triggered several research projects on the dynamics of the blaze. The goal is to determine its hottest points and how that heat weakened the structural steel. According to one calculation, the amount of jet fuel in the aircraft would have burned out in about 10 minutes if spread evenly over a concrete surface the size of one level of the World Trade Center. A member of the ASCE team, Jonathan Barnett of Worcester Polytechnic Institute's Center for Firesafety Studies in Massachusetts, says that the extended burning indicates that the flammable contents of the plane and the buildings themselves were significant factors in stoking the fires until they were hot enough to weaken steel.

Barnett plans to use a computer model to see how the buildings' design (and the broken windows and gaping holes left by the aircraft) contributed to the flow of oxygen to the fires. He also wants to interview firefighters and listen to 911 calls from people describing the fires from inside WTC offices. "It's possible that the structural failure occurred at lower temperatures [than currently assumed]," Barnett told *Science*. "If there are high stresses on the steel, you don't need extremely high temperatures to weaken it."



Collateral damage. Fire and projectiles from the collapse of the twin towers damaged several buildings in and around the World Trade Center complex. These structures may provide clues to the behavior of buildings subjected to less extreme forces than those that brought down the towers.

Another line of inquiry involves the plumes of smoke that emerged from the towers before their fall. William Grosshandler, chief of the fire research division of the National Institute of Standards and Technology's Building and Fire Research Laboratory in Gaithersburg, Maryland, says his lab hopes to use its smoke-plume analysis software to estimate the "rate of heat release" from the fires. "By examining the trajectory and intensity of the smoke plumes, we may be able to work backward to tell the structural people a bit more about the fires," says Grosshandler. But that sort of analysis requires high-quality video and still photos of the smoke plume, which have been hard to come by. His lab did the same sort of heat-release analysis following the Kuwait oil fires lit by retreating Iraqi troops during the Gulf War.

James A. Milke, a member of the ASCE team and the department of fire protection engineering at the University of Maryland, College Park, is looking at the interaction between the fire and the steel columns, using a computer model to recreate their rising temperatures. For that analysis, he needs data on the fire's intensity and the type of steel used in the towers' columns and trusses. The lingering fires in the rubble are making it harder to determine the initial temperature of the fires that attacked the steel and to pinpoint where the metal failure originated. Milke so far has found no previous examples of steel-frame buildings that collapsed after a fire. But he has documented several cases—in Los Angeles, London, and Philadelphia—in which tall steel-frame buildings remained standing in the midst of lengthy fires.

Whereas some other engineers suspect that the failure of bolts connecting floor trusses to columns may have been the first fatal step to disaster after the collisions and fires, Levy thinks that the damage to the inner core of columns—both from the impact and heat—initiated the actual collapses. He suspects that the fireball blast from the burning jet "most likely took away the fire protection that the interior columns had." The twin towers' structural engineer of record, Leslie Robertson of Leslie E. Robertson Associates in New York City, says that all the trusses and columns were "fully fireproofed." But he told the symposium audience that the impact of the aircraft may have stripped the fireproofing from some of the steel.

Will the demise of the World Trade Center towers dampen plans for future giant skyscrapers? Both Thornton and Levy expect to see efforts to make the next generation of big buildings more resistant to blasts and fires. But Levy says the decision to build a superskyscraper is "a political and economic question, not an engineering one." Construction already has begun on a new building in Taiwan that may exceed the height of the Petronas Towers, notes Thornton. And he doesn't think the events of 11 September will alter the plans. "I think they'll keep building it," he says. –ROBERT KOENIG

In the rubble. Engineers examine steel structures from ground zero.

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