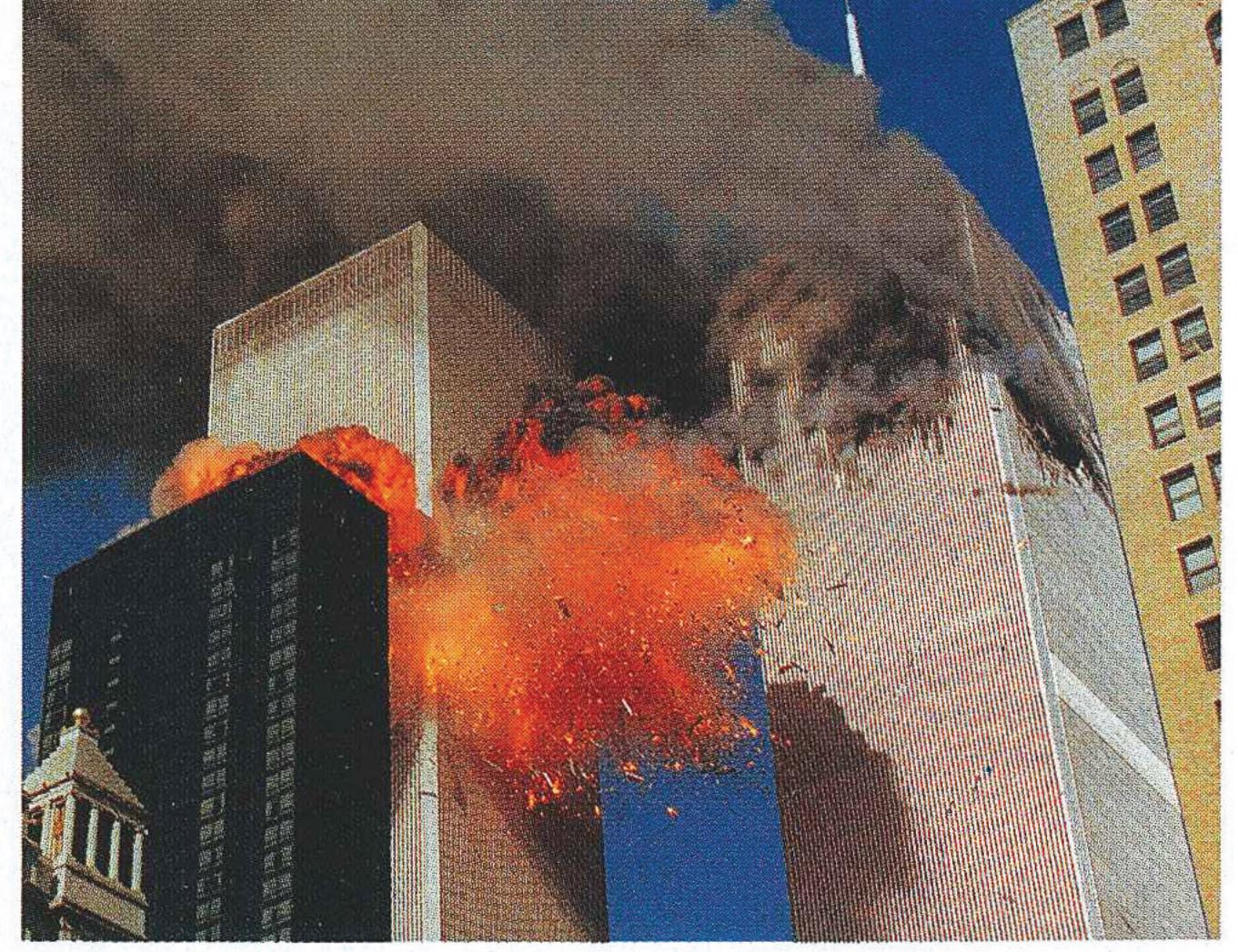
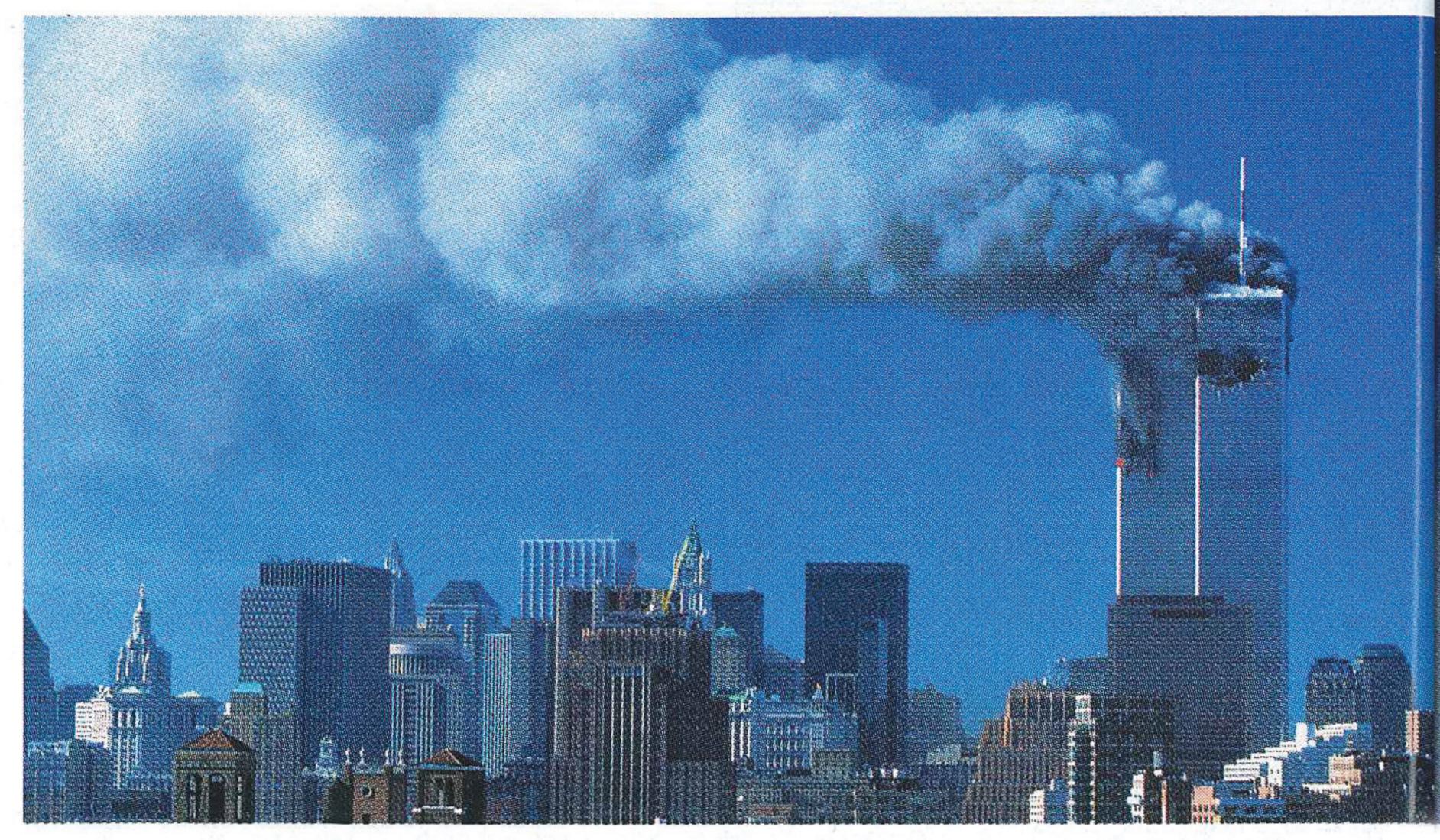
## SPECIAL REPORT







## World Trade Center's Robust Towers Succumb to Terrorism

By Deborah Snoonian, P.E., and John E. Czarnecki, Assoc. AIA

On September 11, the world looked on in horror as the twin towers of New York's World Trade Center collapsed after each was struck by a hijacked commercial aircraft. In the disaster's aftermath, the design and construction community is assisting

cleanup efforts, assessing why and how the structures failed, and discussing the future of skyscrapers and lower Manhattan—while recognizing that few, if any, of the nation's iconic structures can be fully protected from terrorist acts.

Both towers were hit by Boeing 767s en route from Boston to Los Angeles—each heavy with jet fuel for the cross-country flight. The South Tower, known as Two World Trade Center, came tumbling down just under an hour after it

11. Federal Office Building. Cross & Cross and Pennington, Lewis

12. N.Y. Telephone Building. McKenzie, Voorhees & Gmelin, 1927

& Mills, 1935

13. 4 World Financial Center. Cesar Pelli and Haines Lundberg Waehler, 1986

14. 3 World Financial Center. Cesar Pelli and Adamson & Associates, 1985

**15.** The Wintergarden. Cesar Pelli, 1988

16. 2 World Financial Center. Cesar Pelli and Haines Lundberg Waehler, 1987

17. 1 World Financial Center. Cesar Pelli and Adamson & Associates, 1987

18.90 West Street. Cass Gilbert, 1907

Lamb & Harmon, 1912

was hit. The North Tower, or One World Trade Center, collapsed about an hour and a half after the attack. Seven World Trade Center, its integrity compromised by the nearby crashes and explosions, crumpled later in the day. At press time, 276 people were confirmed dead in the attack, and more than 6,400 people were still missing.

Mohamed Atta, the alleged ringleader of the terrorist mission and one of the hijackers of the Boeing 767 that hit the North Tower, reportedly obtained a degree in architecture from Cairo University and studied urban planning at the Technical University of Hamburg-Harburg in Germany. Atta's father has denied his son was part of the attack and has claimed the real hijacker stole his son's identity.

Within a day of the strikes, New York City hired LZA/Thornton-Tomasetti Group, a New York engineering firm, to oversee a team of contractors to conduct inspections of surrounding buildings and keep the disaster areas safe for

recovery workers (see "Local engineers rush to assist removal," page 27). At press time, all seven buildings in the World Trade Center complex had collapsed at least partially, and structural repairs will be needed on three large office buildings: 30 West Broadway, Bankers Trust, and 3 World Financial Center. Other nearby structures sustained extensive facade, window, and soot damage. It will be weeks to months before they can be occupied again.

#### An innovative design

Completed in 1973, the 110-story skyscrapers were designed by Minoru Yamasaki & Associates of Detroit with Emery, Roth & Sons of New York. The North Tower was 1,368 feet tall; the South Tower was six feet shorter. For a brief time, they were the world's tallest buildings, until Chicago's Sears Tower surpassed them in 1974.

The towers were classic examples of tube structures, which gain their strength from tightly spaced perimeter columns that provide wind resistance. Perimeter steel columns, spaced 39 inches on center, were braced laterally by 40,000-square-foot floor

diaphragms of concrete and metal decking on 60-foot horizontal steel trusses extending from the concrete core. The building's central core carried only the dead load of the elevator bank. The open floor plate was unencumbered by any columns from the perimeter to the core.

To preserve floor space on the lower stories, Otis Elevator developed a central network of express and local elevators for the towers, requiring passengers to change elevators at sky lobbies on the 44th and 78th floors—a solution that halved the number of elevator shafts needed.

#### Local damage led to failures

Several groups, including the American Institute of Architects (AIA), the American Society of Civil Engineers (ASCE), and the American Institute for Steel Construction (AISC), have assembled forensic teams to determine exactly how the structures failed. Although the investigation continues, experts point to a likely progressive collapse—a chain reaction of failures triggered by damage to a relatively small portion of a structure.

(continued on page 24)

## In terrorist attack, Pentagon sustains damage in newly renovated area

When American Airlines Flight 77 slammed into the Pentagon the morning of September 11, it left a gaping hole in the southwest side of the structure near the heliport, in an area known as Wedge 1, whose renovation was completed earlier this year as part of an ongoing \$1.1 billion upgrade of the entire Pentagon complex. Reinforcements call for protection against explosion and subsequent progressive collapse, including blast-resistant windows and debris-catching material strung between vertical steel beams installed around each window. Officials believe these improvements helped save the building from further harm and allowed people to escape the damaged area. Many of the blast-resistant windows didn't break at all.

The five-story Pentagon is divided into five wedges, and its offices are arranged in five concentric rings connected by a series of corridors. In the crash area, the building's outermost E- ring collapsed completely, and the worst damage extended into the first and second floors of the B-ring.

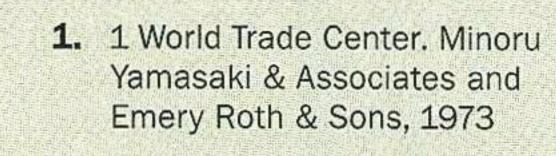
At press time, 30 people were confirmed dead in the attack, and another 159 were still missing.

The idea of housing what was then called the War Department in a single building was conceived in mid-July 1941 by Brigadier General Brehon B. Sommervell, chief of the construction division of the Office of the Quartermaster General. In just a month, the Pentagon was designed by a team of Army engineers, construction experts, and a Los Angeles architect named George Edwin Bergstrom who was a "dollar-ayear" volunteer during the Roosevelt Administration. It was dedicated on January 15, 1943, sixteen months after ground was broken on September 11, 1941—exactly sixty years before the deadly attack.

Still considered one of the world's largest office buildings, the stripped-down-Neoclassical Pentagon was named a National Historic Landmark in 1992. DS

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4. 4 World Trade Center. Minoru Yamasaki & Associates and Emery Roth & Sons, 1977 2. 2 World Trade Center. Minoru Yamasaki & Associates and

5. 5 World Trade Center.

& Sons, 1972

Minoru Yamasaki &

Associates and Emery Roth

3. 3 World Trade Center (Marriott Hotel). SOM, 1981

Emery Roth & Sons, 1973

MANHATTAN

6. 6 World Trade Center. Associates and Emery Roth & Sons, 1974

10. Millennium Hilton. Eli Attia

Architects, 1992

7. 7 World Trade Center. Emery

Roth & Sons, 1978 8. 1 Liberty Plaza. SOM, 1974

9. East River Savings Bank. Walker & Gillette, 1934

19. Bankers Trust Bank. Shreve

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#### GONESO FAST

The World Trade Center had a total of seven buildings, including the two towers. The whole complex had more than 10 million square feet of office space, seven times the area of the Empire State Building.

The ground breaking was held August 5, 1966. A ribbon cutting ceremony was held April 4, 1973.

The Port Authority of New York and New Jersey built the towers.

Both towers were 110 stories tall. Tower One (completed in 1972) was 1,368 feet tall and Tower Two (completed in 1973) was 1,362 feet tall.

The twin towers were the world's tallest buildings until Chicago's Sears Tower was completed in 1973.

Each tower had 104 passenger elevators and 21,800 windows.

In strong winds, each tower swayed approximately three feet from true

Each tower's foundation extended more than 70 feet underground to rest on solid bedrock.

The ground-level World Trade Center Plaza was larger than Venice's Piazza San Marco.

More than 50,000 people worked in the World Trade Center, which was home to more than 430 companies from 26 countries.

An estimated \$10 million worth of art was destroyed in the disaster, including Alexander Calder's 25-foot-tall "Three Red Wings" stabile and Miró's "World Trade Center Tapestry."

WTC cost \$1.5 billion in 1973 dollars.

(continued from page 23) Progressive collapses are a common mode of failure for buildings that suffer severe local damage, such as that caused by an explosion; the Murrah Federal Building in Oklahoma, which was bombed in 1995, is one example. "From what I've seen, the collapse of the towers was a classic case of this sort of

failure," said Norris Stubbs, a profes-

team that examined the World Trade

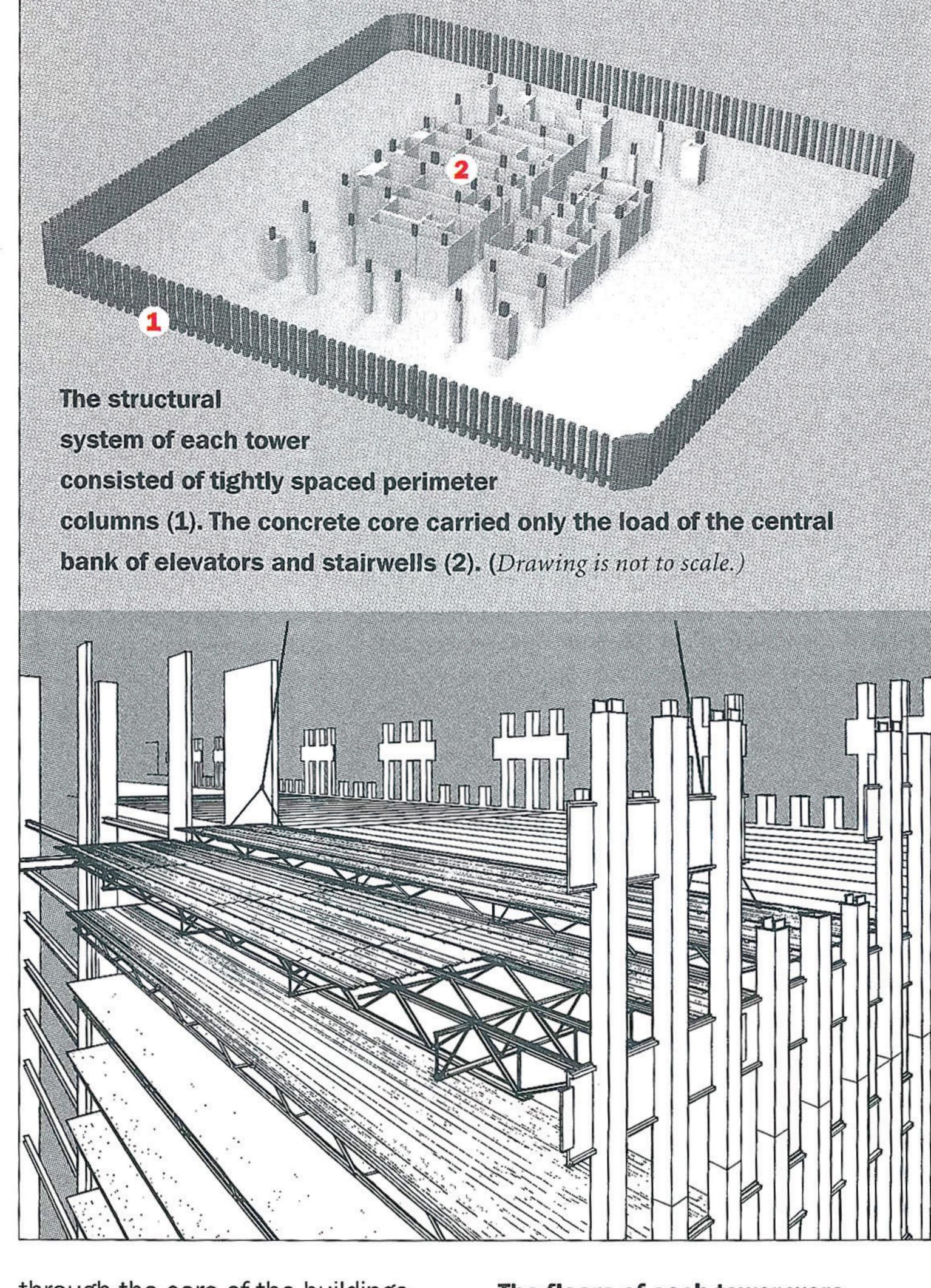
sor of civil engineering at Texas

A&M University, who was on the

Center after the 1993 bombing.

The crashes destroyed columns and floors on several stories of each tower, which transferred abnormal, excessive loads to the remaining columns. "It appeared that the floor systems lost their connection to the exterior columns," observed Jon D. Magnusson, chairman and CEO of Skilling Ward Magnusson Barkshire, a successor firm to the towers' original structural engineer, who is serving on the forensic teams for ASCE and AISC. "Since the floors provided the perimeter columns with resistance against buckling, the columns would have begun to lose lateral stability," said Stubbs.

The explosions and raging fires severely weakened the remaining columns, which were already overloaded by the breaches caused by the crashes. "Jet fuel releases much more heat than paper and plastic, which typically fuel office fires," said David A. Lucht, director of Worcester Polytechnic Institute's Center for Fire Safety Studies. Fireproofed steel loses half its strength when it reaches 1,100°F and fails rapidly above 1,600°F; temperatures inside the building were likely even higher. In an interview with CNN, Aaron Swirsky, one of the original architects with Minoru Yamasaki & Associates for the towers, theorized that jet fuel may have leaked down



through the core of the buildings, possibly causing more explosions and fire damage than could be seen from outside.

The steel columns, weakened by fire, finally buckled, and the floors they supported dropped on top of one another in a "pancaking" action. Each falling floor overburdened the columns and floors below it, causing the buildings to tear themselves down. Video footage of the South Tower showed that the top of the building above the breached area began to topple over just before the floors below it gave way and triggered a full collapse.

If fire proves to be the primary culprit for the failures, the World Trade Center disaster will be the first known failure of American skyscrapers due to fire. Structural damage to the towers from the 1993 bombing was relatively minor and was fixed, said Stubbs, who believes this damage did not contribute to the collapses.

The floors of each tower were unencumbered by columns from the perimeter to the central building core, as shown in perspective drawing above. (Drawing is not to scale.)

#### Design was adequate

Project engineer Leslie A. Robertson's statement that the towers could survive being struck by a Boeing 707, a smaller plane with a much lower fuel capacity, have been recalled since the disaster. Experts acknowledge that the very nature of the design of the towers allowed them to withstand the crashes without toppling instantly. "The planes ripped huge holes in the buildings, but there were many remaining columns that were strong enough to bridge those holes, and they held up the rest of the structure for a time, which let many people get out," Magnusson said. Some speculate that if the towers had been struck lower, the force of the crashes

(continued on page 26)

## Rebuild the WTC towers? Death of the skyscraper? Architects and engineers weigh in

RECORD asked architects and engineers who have had an interest in the World Trade Center and the design of tall buildings, What is the future of the WTC site? What impact does this event have on the future of skyscrapers?

"It would be entirely appropriate to have the Trade Center reproduced at this site. If we turn the site into a memorial, in a way, it would be a monument to the success of terrorism."

-HENRY GUTHARD, SENIOR VP WITH MINORU YAMASAKI & ASSOCIATES, AND A MEMBER OF THE ORIGINAL WTC DESIGN TEAM

"They ought to rebuild the [WTC] buildings, but not necessarily as targets. I don't think Americans should be swayed by what those bastards did."

-BRUCE GRAHAM, FAIA, SOM LEAD ARCHITECT FOR CHICAGO'S JOHN HANCOCK CENTER AND SEARS TOWER

"Rebuilding the WTC as it was would be showing nostalgia for a world that doesn't exist. What has happened with the media coverage shows we don't need monuments. Buildings no longer contain memory. The media contains that memory. So we need to build again with the understanding that we don't want to build the same buildings."

-PETER EISENMAN, FAIA

"It changes our thinking about [skyscrapers], no doubt about it. There was nothing wrong with the conceptual design [of the WTC towers]."

> -WILLIAM LEMESSURIER, STRUCTURAL ENGINEER FOR MANHATTAN'S 59-STORY CITICORP CENTER

"The only way to demonstrate our strength would be to build two towers of similar size. I don't see why we should capitulate to a group of criminals."

> -CESAR PELLI, FAIA, ARCHITECT OF THE NEARBY WORLD FINANCIAL CENTER AT BATTERY PARK CITY

"The site has to be rebuilt. **Economics will dictate what** goes there."

> -CAROL ROSS BARNEY, FAIA, PRINCIPAL, ROSS BARNEY + JANKOWSKI, ARCHITECT OF THE GSA'S NEW FEDERAL CAMPUS IN OKLAHOMA CITY

"The future of the tall building will have to receive scrutiny regarding its structure and life safety systems. The tall building is a fundamental component of dealing with density, and it will continue to be."

-WILLIAM PEDERSEN, FAIA, PARTNER, KOHN PEDERSEN FOX

"I don't know that the twin towers should be rebuilt. Perhaps an even more spectacular skyscraper with its own distinct form would be better. On the other hand, there is much to commend in rebuilding Yamasaki's building." -ROBERT A.M. STERN, FAIA

"I hope that they rebuild, whether they rebuild that exact structure or not. To turn it into a park does not capture the essence of what New York is. It's about density and bustling sidewalks, and that's the nature of the city."

-KENNETH T. JACKSON, EDITOR OF THE ENCYCLOPEDIA OF NEW YORK

'I suspect the design criteria [of tall buildings] may change in the future. I'm not sure that height is an issue, though."

-RICHARD GREEN, FAIA, CHAIR AND CEO OF STUBBINS ASSOCIATES

"Whatever is built on this site will say more about us as a people and how we see our future than about concrete, steel, and

glass. The WTC should be redeveloped as a strong symbol of America's resolve.

> -EDWARD A. FEINER, FAIA, CHIEF ARCHITECT OF THE U.S. **GENERAL SERVICES** ADMINISTRATION (GSA)

"Unquestionably there will be a [short-term] stop [in plans for tall buildings]. This is inevitable. [But] the desire to build very

also assert a positive plan to rebuild 12 million square feet of mixed-use and commercial space on the site."

—CAROL WILLIS, DIRECTOR OF THE SKYSCRAPER MUSEUM, NEW HOME TO BE BUILT NEAR THE WTC SITE

"It was a great symbol. I'll be very disappointed if we end up with a park on that site. There should be something as dra-



high and slender buildings is so ingrained in the way we are. Tall buildings will be built with great care and consideration."

—CESAR PELLI, FAIA

"Any building, whether it's low or high, is vulnerable. Terrorists don't discriminate. They will find a way." -MIR ALI, PROFESSOR,

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN SCHOOL OF ARCHITECTURE AND EXPERT ON TALL **BUILDING DESIGN** 

"Reimagining the city would be the best memorial, not a permanent hole amid the streets of

-HUGH HARDY, FAIA

"There will certainly be a memorial planned for the site. I think the most eloquent one might be two squares, each an acre of grass marking the footprint of the former towers. But respecting their absence, we should

matic built—tall or even taller. Something has to rise on that site. I'm still very optimistic on building tall buildings."

-JOHN SHEEHY, FAIA, RIBA, PRESIDENT OF ARCHITECTURE INTERNATIONAL AND A MEMBER OF THE SOM DESIGN TEAM FOR CHICAGO'S HANCOCK CENTER

"We may take a break from building such giants, but given their symbolic value and given time to regain our confidence, I think skyscrapers will inevitably remain a sign of the achievement of our civilization."

-EDWARD A. FEINER, FAIA

"The notion of the [tallest] skyscraper as a singular icon may have seen its day because of its vulnerability. It has become such a target, and it doesn't make much sense anyway."

-BRUCE FOWLE, FAIA, PARTNER, FOX & FOWLE ARCHITECTS

## SPECIAL REPORT

(continued from page 24) would have exceeded the buildings' resistance to overturning and they would have come down immediately, endangering nearby buildings as they fell.

"There was absolutely nothing wrong with the conceptual design of the towers," said William LeMessurier, the structural engineer for New York's 59-story Citicorp Center. "No one could anticipate the extraordinary impact, fuel load, and resulting fire."

Other skyscraper design solutions probably would not have fared any better. "[The towers] were very robust structures," said Mir Ali, professor of architecture at the University of Illinois at Urbana-Champaign and an expert on tall building design. "The design solution used probably wouldn't have mattered, given the nature of the crash." A structural system using a central core for wind resistance, for instance, would have had perimeter

columns spaced at least 10 feet apart—a common design technique for highrises. But, Magnusson said, "if the crash destroyed a central core, as it likely would have, there wouldn't have been enough exterior columns to support the structure afterward. It's likely such a building would have fallen right over." Designers agree that

few structures, no matter what their height, can endure such aggressive attacks. "Only a nuclear containment vessel or a missile silo is designed to withstand that kind of impact and fire," said Robert Solomon, chief building fire protection engineer for the National Fire Protection Association. Even buildings reinforced to withstand blast loads, such as the area of the Pentagon struck in the attack (page 23), aren't entirely safeguarded against damage.

World Trade Center since it opened in the early 1970s, feels very lucky. All of

the firm's 140 employees survived the September 11 disaster without a sin-

gle injury, and most were back to work three days later in a temporary office.

Hannaford, chief financial officer and principal at Mancini Duffy. The firm

had an office in Tower One until the 1993 bombing, and had space on the

September 11, Hannaford was checking his e-mail when he heard a loud

boom. Colleagues on the other side of the office gasped as they saw a fire

high above in nearby Tower One—a plane had hit it. "My initial reaction was

that I had no idea what happened," Hannaford said. "From our view, it did not

appear that there was extensive damage. I honestly thought some lunatic

building as they watched the top of the adjacent tower burn, took their own

Mancini Duffy employees, who did not hear any announcement in the

21st and 22nd floors of Tower Two since then.

"We did not lose any people and we are very fortunate for it," said Dave

The new location did not guarantee peace and calm. On the morning of



#### Twin icons, vanished

The absence of the twin towers dramatically changes New York's skyline. Cesar Pelli, FAIA, designed the World Financial Center at Battery Park City with the World Trade Center as its backdrop. "It doesn't feel right or appropriate that those buildings are now set against only the sky," he told RECORD.

The attack will also have major consequences for other buildings planned for the city. In the week fol-

before we realized we should get out of the building."

lowing the disaster, it was already apparent that New York's building boom will be stalled by the disaster. Skilled laborers, including ironworkers, crane operators, and carpenters, left the city's major construction projects to help in the rescue and recovery efforts. The need for workers to quickly retrofit office space for displaced companies will further worsen the city's shortage of skilled workers. Major

(continued on page 28)

# All 140 Mancini Duffy employees survive WTC disaster unscathed, back to work in three days Mancini Duffy, an architecture firm that has maintained an office in the us what to do. We actually milled around the lobby for several minutes

With debris falling from the sky, they dispersed into the streets. Hannaford headed east and watched the scene unfold a few blocks away. Within minutes, a plane hit Tower Two, the building that Hannaford had just evacuated. He said he didn't actually see the plane hit, but did see the huge explosion and fireball. Bewildered and unsure of exactly what had happened and intent on leaving the area, Hannaford just kept walking east and then north away from the towers, eventually reaching midtown. As he walked farther away, he saw the towers collapse, barely stopping on his way to a ferry across the Hudson, to eventually reach his New Jersey home.

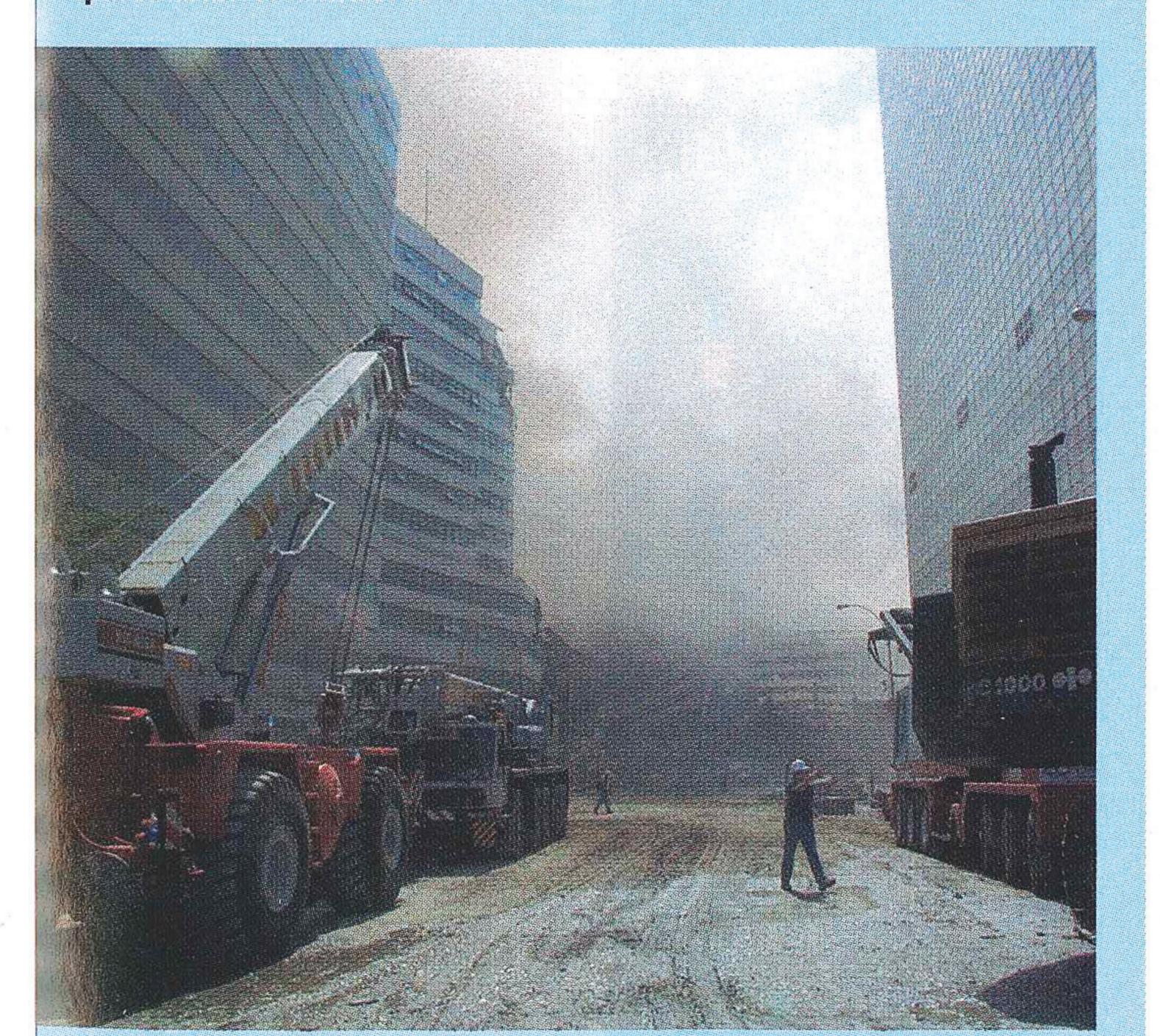
That evening, Mancini Duffy principals contacted each other and made plans for a meeting on the following afternoon. Relieved with news that all employees were safe, firm leadership quickly accepted an offer from their client, JP Morgan Chase, to take office space at 277 Park Avenue. Most employees attended a company meeting on the Thursday after the disaster and were back at work in the temporary office on the next day. The following initiative and headed for the fire exits. "We proceeded down the stairwell in week, new computers were in place and a new permanent office was prorelative calm. It probably took about 10 minutes to get out of the building, cured. CAD files were retrieved from previous clients, and financial data was and it was a crowded but orderly exit." Hannaford said. "Once we got down to recovered from an off-site archive. Hannaford said, "We just want to get the lobby, we saw a tremendous amount of debris landing, but no one to tell back to work and start rebuilding the firm." John E. Czarnecki, Assoc. AIA

Local engineers rush to assist removal

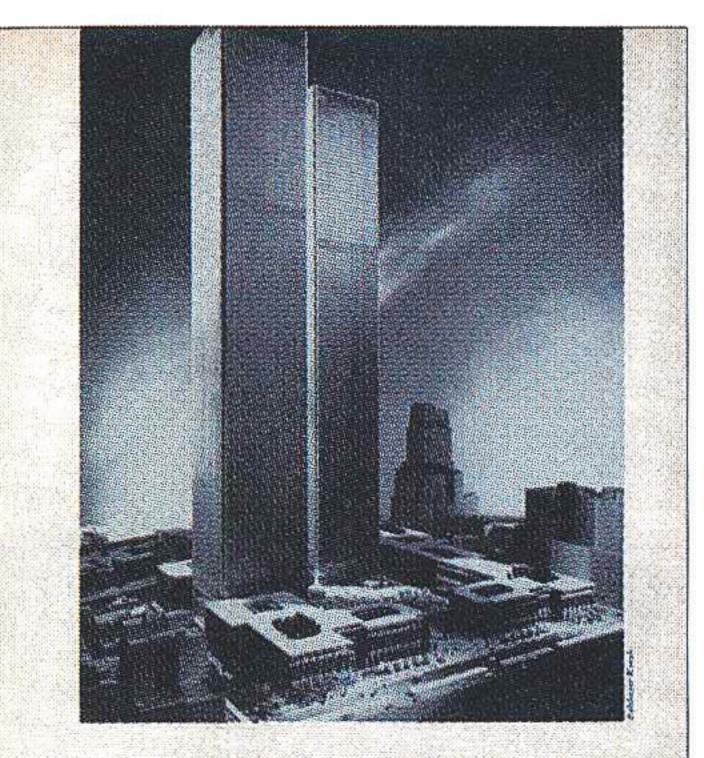
There has been no shortage of volunteers in The Hole, as some refer to the 800,000 tons of wreckage, 100 feet deep, of what used to be the World Trade Center. At press time, a new group had mobilized to assist in the perilous demolition and removal process. Coordinated by the Structural Engineers Association of New York (SEAoNY), at least 150 volunteer engineers joined the effort led by the New York City Office of **Emergency Management, the New York City Department of Design and** Construction, and the New York City Building Department.

SEAoNY's mission has been twofold, the first taking place at ground zero. The site was divided into four quadrants, each assigned to a different contractor to handle the demolition and removal. Teams of three engineers were rotated through each quadrant in 12-hour shifts. Their task was to advise the contractors on the most stable places to erect cranes and to operate heavy machinery. They also helped determine the safest sequence of removal, especially of large pieces of steel and concrete that have the potential for causing further collapse. "We are another set of eyes," said one SEAoNY officer, referring to the surgical nature of the operation.

The second part of the mission was forensic, a structural triage of sorts. Teams of engineers completed a visual inspection of some 350 buildings around the perimeter of the disaster site. The engineers used the ATC-20 system, an evaluation system developed by the Applied Technology Council for on-the-spot decisions regarding continued use and occupancy of buildings that have been damaged by an earthquake. First established in 1989 and revised in 1995 and 1997, the guidelines were specifically intended to enable volunteer structural engineers and building inspectors make a rapid and detailed assessment of buildings that may be at risk. At the WTC, buildings were graded and given a preliminary color code: green (apparently safe), yellow (limited entry only), or red (unsafe). A second round of inspections and more in-depth investigations will be required for any buildings marked yellow or red. In the meantime, volunteer engineers have continued to work doggedly around the clock, at considerable personal risk. Sara Hart



## Yamasaki's World Trade Center boasted an embattled, remarkable history



erals in the face of the towering office blocks.
Of the 10 million square feet of rentable space, about

ABUTTETETURAL RICCHO February 1924

con buildings will house exhibition space and a botel, electrical. The owner is the Port of New York Authority Further details on the center will be given in a fort

In 1962, when Minoru Yamasaki was given the commission to design a World Trade Center on the lower west side of Manhattan, the plan had already been through years of tortuous New York politics, evolving from David Rockefeller's commitment to help the city's then moribund financial district. In 1960, Rockefeller recommended that a study be led by the local Port Authority, turning a private project into a public one, and involving Rockefeller's brother Nelson, then governor of New York.

Yamasaki worked with Emery Roth & Sons on the towers, and SOM designed a hotel. Names originally considered for the project include Bunshaft, Harrison, Stone, Gropius, Johnson, Pei, and Kahn.

Critics' reactions were mixed. Ada Louise Huxtable, architecture critic of the New York Times, originally liked the towers, though she later revised her opinion, calling them "the biggest, daintiest buildings in the world. There was no substance." Lewis Mumford accused them of "purposeless gigantism."

The towers entered modern mythology in 1972, when a skydiver landed on the roof. In the same year, another man safely parachuted from the top down into the plaza. The aerialist Philippe Petite once crossed between the towers on a tightrope, before being

arrested. And in 1977, George Willig scaled Tower One.

On February 26, 1993, a truck filled with explosives blew up in a parking garage below the towers. The terrorists had planned to topple one tower into the other. Six people were killed and 1,000 others injured, but the buildings reopened.

Sportswriter Roger Kahn wrote in The Boys of Summer of his expe-





The WTC design by Yamasaki (top with model) was in the February 1964 issue of RECORD (top left).

rience atop the towers during construction (where he tracked down former Brooklyn Dodger Carl Furillo at work for Otis Elevator):

"Wind was slamming across the Hudson, blowing bits of debris from unfinished floors. Four thousand men had been working for two years, and the sprawling site had acquired the scarred desolation that comes with construction or with aerial bombardment." Kevin Lerner

brought a bomb to work."