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Serving the International Materials Research Community

A Publication of the Materials Research Society

September 2007, Volume 32, No. 9

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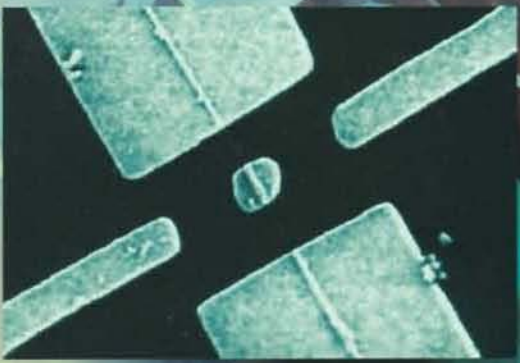

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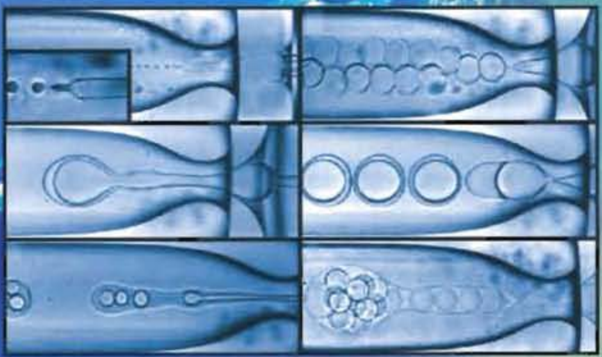

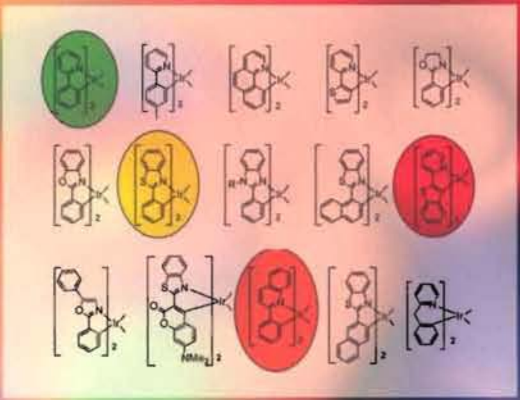

Organic Light-Emitting Devices

WTC Collapse: A Metallurgist's View

The Collapse of the World Trade Center Towers: A Metallurgist's View

Frank W. Gayle

Abstract

This article is based on an edited transcript of a presentation given by Frank W. Gayle (National Institute of Standards and Technology) on April 12, 2007, in Symposium X at the Materials Research Society Spring Meeting in San Francisco.

The NIST investigation of the World Trade Center disaster addressed many aspects of the catastrophe, from occupant egress to factors affecting the ability of the Twin Towers to remain standing after being hit by the airplanes, with the goal of gaining valuable information for future best practices in building materials, building design, and emergency response. The presentation addressed the structure of the towers, the analysis of the recovered steel, and special issues faced during the investigation. The probable collapse sequence for each of the towers was also discussed.

Introduction

It is a pleasure to be here today. I want to thank the organizers for inviting me to present this work from the NIST World Trade Center investigation. I headed up the metallurgical analysis of the steel recovered from the World Trade Center, and I particularly want to acknowledge the researchers and engineers of the NIST Materials Science and Engineering Laboratory who applied their hearts, souls, and weekends to this challenge for four years.

The World Trade Center Towers stood out as enormous buildings, even among the neighboring skyscrapers in lower Manhattan, for both their height (110 stories) and width (approximately 207 feet). Following the events which brought the towers down on September 11, 2001, NIST was directed by Congress to investigate and determine the details of the towers' collapse following the impact of the aircraft and the ensuing fires. The investigation, led by the NIST Building and Fire Research Laboratory, consisted of eight projects with over 200 active participants and was completed in September 2005. NIST's primary objective was to learn all that it could from this tragedy, and to extract some good where possible.

NIST also took the opportunity to step back and reassess building codes and practices for tall buildings. Many building codes were developed for 10-story buildings, yet are still being used today for 100-story buildings. For example, there was the implicit expectation that a firefighter would be able to run from the first floor all the way to the top of a tall building and fight a fire, whereas in a 100-story building that is not practical in any reasonable length of time. In contrast, some buildings in Europe have special elevators, made of hardened materials and with advanced ventilation systems, for firefighters to use in emergencies. So it was an opportune time to assess various practices that perhaps should be changed.

Today, I will focus on two aspects of the overall NIST World Trade Center investigation: the steel recovered from the site, and modeling of the events of September 11, 2001.

Structure of the Twin Towers

Early in the investigation, an understanding of the structure of the buildings was a high priority. The towers were complex in some ways, and had many innovative features. The buildings contained three sections, separated by mechanical (equipment) floors and "sky lobbies." The design included express elevators to the sky lobbies, where occupants would then take local elevators to their destination. The innovative "express plus local" elevator approach was a necessary concept, since a conventional elevator layout would have required many more elevators and would have occupied about half of the entire floor plan in the lowermost levels of the building.

The building plan included enormous interior open spaces, about 60 feet wide and 200 feet across, very attractive for column-free office space. A lightweight floor truss system supported the expansive floors and bridged between the perimeter columns and the core of the building, which contained the engineering and mechanical support systems. The truss system was used instead of conventional beams to bridge the 60 feet from the perimeter to the core to decrease the weight and to facilitate a modular design. Trusses were prefabricated into panels with the metal deck and hoisted into place before a 4-in.-thick layer of lightweight concrete was poured for flooring. Above the ninth floor, the perimeter columns were spaced 40 inches apart, running from the ninth floor to the 107th floor. These perimeter columns supported about 40%–50% of the gravity load and all of the wind loads for the buildings.

Another innovation was the prefabrication of many of the parts that went into the building. Perimeter panels (Figure 1), 10 feet wide by 36 feet tall, were prefabricated on the West Coast by Pacific Car and Foundry, a railroad car manufacturer. These panels, three columns wide and three stories tall, were hoisted into place and bolted to columns below. Spandrels were then bolted to adjacent panels. In a conventional building, a spandrel is a beam that runs around the outside of the building; in this case, the spandrel was a deep, flat plate that along with the columns gave enormous rigidity to the structure. Ultimately, the rigidity allowed loads to be transferred right around the holes in the buildings created by the airplanes on September 11, 2001.

The perimeter columns were made of 12 different grades, or strengths, of steel. The 1960s, when the towers were designed and built, were a very rich time for the development of new alloys. The WTC designers made use of some of the very high-strength steels that had just become available. In contrast to the

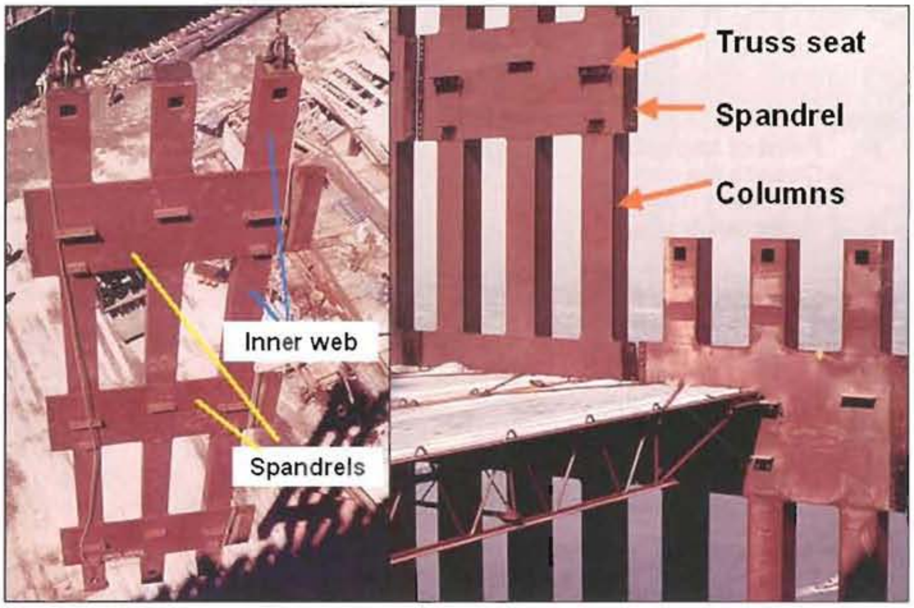

Figure 1. Modular, prefabricated perimeter panel and floor truss structures during construction of the World Trade Center Towers. Perimeter panels are 10 feet wide by 36 feet high. Perimeter panels, three columns wide and three stories tall, were hoisted into place and bolted to adjacent panels. Floor panels, typically 20 feet wide and 35 feet or 60 feet long, were then positioned onto the truss seats. (Photo source unknown. Enhanced by NIST.)

12 grades of steel used in the towers, most buildings, even today, tend to use just two or three grades, and typically only modest strength, around 50 ksi (thousands of pounds per square inch of load before a permanent deformation in tension or compression). The WTC designers specified strengths of up to 100 ksi. The distribution of steel strengths in the perimeter columns consisted of a complicated, asymmetric arrangement, the pattern being different for each of the eight sides of the two buildings. Figure 2 shows an illustration of the section of the South Tower (World Trade Center 2, the second to be hit and the first to collapse) that was struck by the aircraft, with the grades of steel in the columns and spandrels color-coded. In this one area alone, the aircraft entering the building hit all 12 grades of steel—this fact defined the scope of our analysis to include all of the grades of steel used in the building.

The core columns, on the other hand, were of two types: enormous box columns were used in the lower parts of the building, and "wide flange" columns were used in the higher floors. The core columns were designed to absorb only gravity loads and no shear loads due to wind. Most of the columns were fabricated with conventional, lower-strength steels with 36 ksi or 42 ksi strength. Many of the transitions from box columns to wide-flange columns occurred in the 80th and 83rd floors, which were impact floors in the South Tower.

One other key feature of the building structure was the hat truss in the top four floors, floors 107 to 110, of both buildings. This three-dimensional truss system tied the perimeter columns to the core. The hat truss was designed to support the antennas that were intended for both buildings. It was actually added late in the design, and an antenna was installed only on the

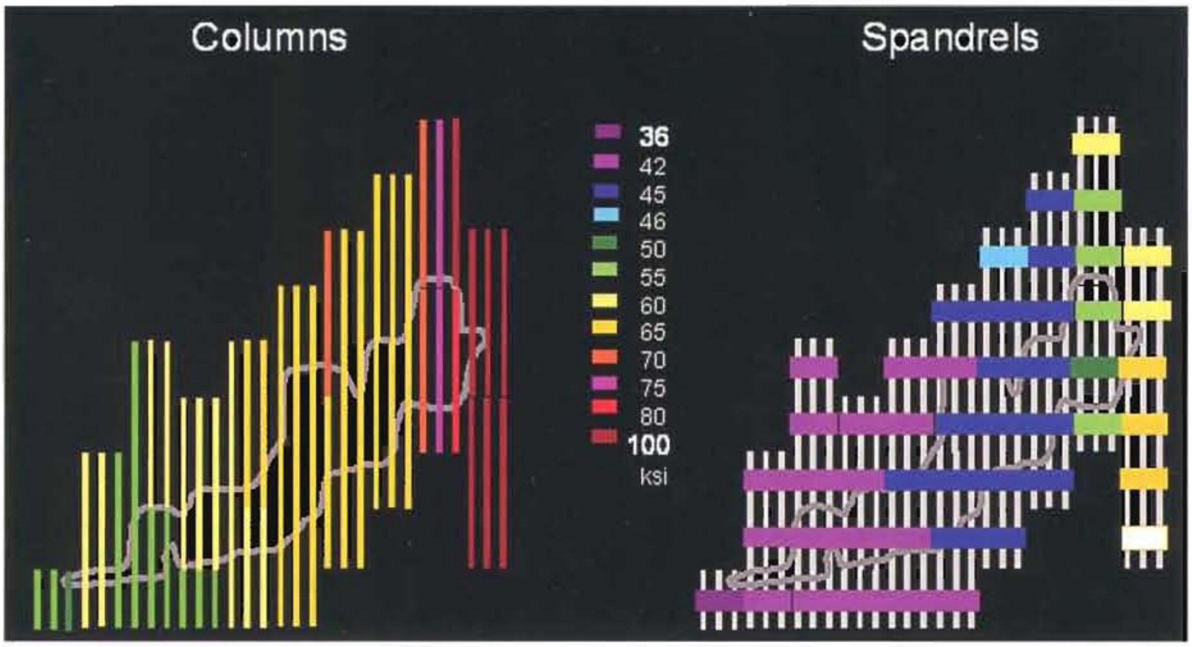

Figure 2. Grades, or strengths, of steel impacted by the aircraft on the south face of the South Tower (World Trade Center 2). All 12 grades of steel used in the perimeter panels were involved in the airplane impact.

North Tower, World Trade Center 1. You will see later how critical the hat trusses were to the performance of the buildings on September 11.

Inside the building, the enormous open spaces that were very attractive for office use were not as good for fire protection. Normally, it would be desirable to have fire-rated walls separating various areas of a floor for compartmentalization and to stop the propagation of fire. However, the buildings had many single-tenant floors with a large number of cubicles but with few walls.

September 11, 2001

On September 11, 2001, airplanes flew into both buildings. The North Tower was hit first, between the 93rd and the 99th floors. The building stood for one hour and 42 minutes after impact. The South Tower was hit 15 minutes later, at a lower level, and remained standing for about half as long, 56 minutes. At first glance, one might guess that the lower floor was supporting more weight and thus collapsed earlier. But the lower columns were stronger, which means the floor level of impact might not have made much difference in the collapse time of the building.

What did make a difference was the speed and orientation of the planes with respect to the buildings, particularly the core, as they impacted the towers (Figure 3). On the North Tower, the plane hit the very center of the north face and continued through, damaging the core, but in a very symmetric manner, and loads were redistributed across the damage in the center of the core. In the South Tower, the plane came in at an angle, and the rectangular core was oriented 90° relative to that of the North Tower. Upon entry, the plane destroyed the corner of the core, and because it damaged one of the massive corner columns, there was much less capability to redistribute loads within the core. This more extensive damage to the South Tower gave it less residual strength and caused it to collapse first. The hat truss then played a critical role, allowing loads from the damaged core columns to be transferred over to the adjacent side walls of the perimeter.

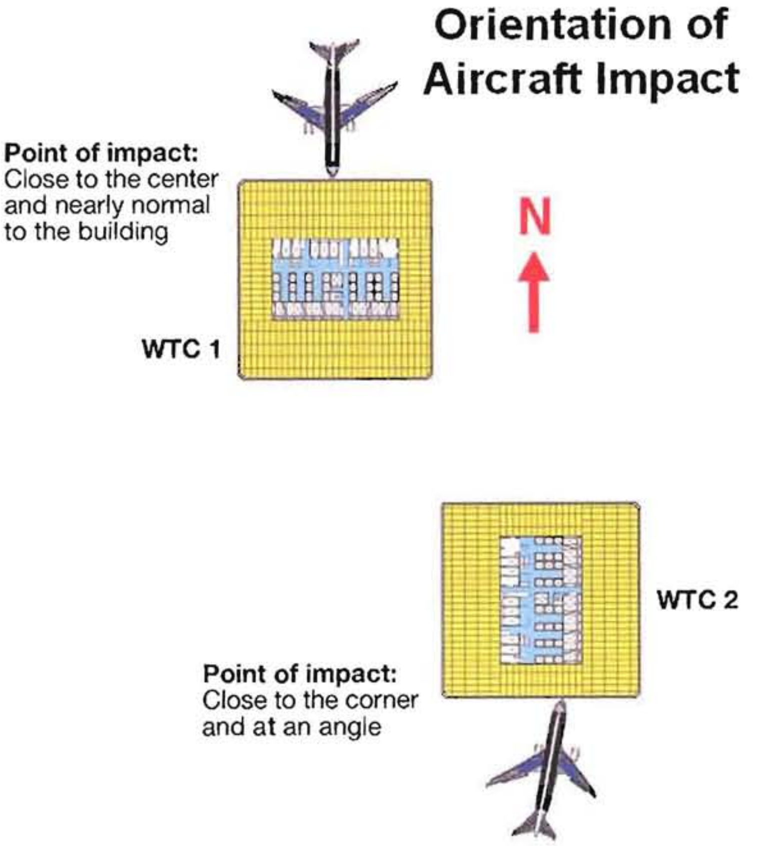

Figure 3. Aircraft impact angles and positions for the two towers. Damage to the South Tower (WTC 2) was more severe than to the North Tower (WTC 1), since a corner of the core was severely damaged, making it difficult for loads to transfer from severed columns to adjacent columns. In WTC 1, the plane was traveling approximately 440 mph; in WTC 2, 540 mph.

Recovered Steel

The first few weeks after September 11, 2001, were a very difficult time in New York City. With respect to the building structure, the collapse resulted in a pile of structural steel about 200 feet deep. It was an enormous job just to get it removed from the site. Some of the pieces weighed as much as 25 tons; it was a tedious process to assess them and remove them safely without causing injury. The steel was shipped to four salvage yards, one on Staten Island and three in New Jersey. Figure 4a shows the giant columns in the pile; the thought of extracting any useful pieces of steel out of that—particularly any specific pieces of steel—seemed rather daunting. The Structural Engineers Association of New York (SEAoNY) volunteered thousands of hours, both on the World Trade Center site and at the salvage yards, looking through the pieces. A member of the NIST team worked with SEAoNY in going through the steel, and even before we were officially charged with the investigation, potentially useful pieces of the steel were shipped to the NIST site in Gaithersburg, Maryland, for storage.

Materials arrived at NIST within a few months of September 11. Much of the steel was damaged but the amount of damage varied. Some of the column sections were in fairly good shape. In contrast, the floor truss materials, after being flattened in the collapse, had to be cut in pieces and balled up to get them off the collapse site (Figure 4b), so they were not in very good shape by the time they were delivered to NIST. But overall, NIST got a very good selection of steel, including all 12 grades of the perimeter panels and four pieces from the north face of the North Tower that were directly hit by the nose of the airplane, the upper part of the fuselage, or the wings (see Figure 5). Identification was aided by serial numbers on the steel pieces in some cases and by the geometry of the plates used to fabricate the columns in others.

One of the NIST team's first jobs was to determine the steel quality. In the 1960s, there was quite a bit of controversy when the contract for most of the perimeter steel went to Yawata Steel (now Nippon Steel) in Japan, since a reputation for quality had not yet been completely established in that post-war era. Part of NIST's task was to assess the quality with respect to the expectations of the designers: Were the design strengths met? What quality should be expected in 1960s-era steel practice? Also, with all of these different grades of steel, NIST wanted to determine if the right steel was in the right places.

Figure 4. (a) Core columns, perimeter columns, and beams from the Twin Towers in a salvage yard in New Jersey. Critical pieces for the NIST investigation were recovered here. (b) Typical condition of the floor trusses in the salvage yards. The lightweight trusses were severely damaged during the collapse. Furthermore, since bridging trusses had been welded to the main trusses in a full-floor cross-grid system, the trusses had to be cut up and compacted in order to remove them from the collapse site.

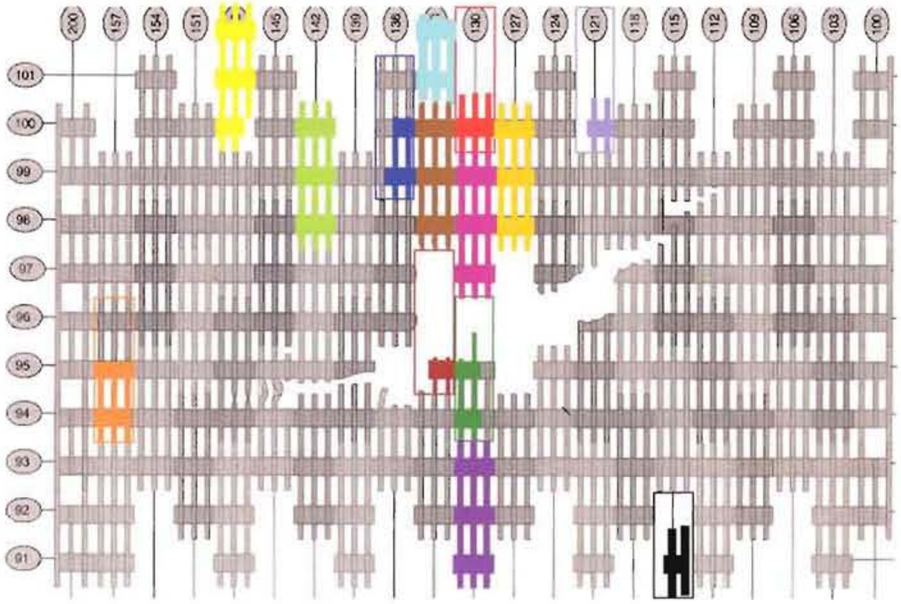

Figure 5. Map of the north face of the North Tower, showing perimeter column panels (in color) recovered and positively identified for analysis in the NIST investigation. These panels included four hit directly by the airplane, providing the opportunity to examine steel performance under high-speed impact. Other panels were used to establish baseline properties of the steel and performance under the high-temperature conditions expected in the fires.

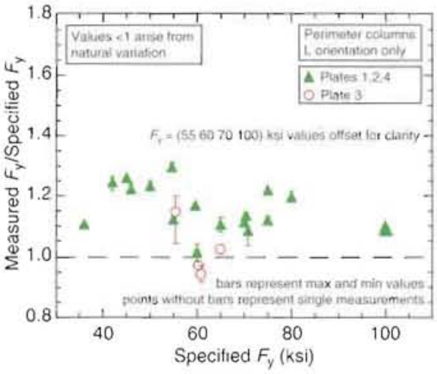

Figure 6. Measured yield strength as a fraction of the specified strength for steel in the perimeter columns. Plates 1, 2, and 4 (triangles) were column panels, and plate 3 (circles) was a spandrel. Ratio values of less than 1 arose from natural variation in the steel and did not affect the safety of the towers on September 11, 2001.

To answer some of those questions, Figure 6 shows a plot of the measured yield strength divided by the specified yield strength for the perimeter columns. Note that some strengths fall below the minimum values, but there are a number of innocuous reasons for that. During the 1960s, a fairly wide strength distribution was allowed in a production lot of steel. Also, once steel has been damaged even a slight amount, it loses an anomalous phenomenon called a yield point, and that will reduce the nominal strength by a few ksi. Finally, the original test procedures could not be reproduced with the damaged steel, which again would result in somewhat lower test values. So, the observed values were not unexpected, and overall the quality of the column steel was determined to be acceptable.

The truss components were made by Laclede Steel in St. Louis. When the NIST team visited Laclede, they were provided several boxes of documents from the company's truss fabrication program. The team talked with one of the engineers who had worked on the project, gaining insight into the truss fabrication process. NIST not only wanted to know whether the material met the minimum strength, but also needed to know just how strong it was, so that the NIST models of building performance would be accurate. The NIST team learned that in practice Laclede routinely substituted 50 ksi steel where 36 ksi steel was called for in the drawings, solving the mystery of why the NIST tests showed that the Laclede steel was much stronger than expected.

Modeling Building Performance

The NIST Building and Fire Research Laboratory modeled all aspects of the event, including the airplane impact, spread of fire, and building response to both. For the finite element models, NIST had to determine and model materials properties, including complete stress–strain curves, and fracture behavior for each grade of steel. There were actually far more than 12 steels in the building; each grade of steel made by a different manufacturer had different properties, and NIST characterized each one individually. All in all, NIST characterized and modeled full stress–strain behavior for 33 different steels.

In addition to static strength, steel under high deformation rates, such as the impact of a plane, exhibits a significant increase in yield strength, thereby increasing the energy absorbed during deformation. An increase in strength and absorbed energy in the steel in the perimeter columns would tend to reduce the amount of energy available for the airplane to do damage inside the building. Without a detailed understanding of how much the airplane was slowed down by the perimeter columns, there couldn't be an accurate model of the internal damage nor, consequently, an accurate prediction of how the buildings responded to the fires. Thus, NIST characterized the various steels with respect to behavior at high strain rates.

High-temperature behavior of the steel, of course, was a very important consideration in modeling building response to the fires. It is important to understand that the fires did not melt the steel; building fire temperatures typically do not get above about half the melting point of steel. However, steel loses strength at temperatures found in a fire, typically 400°C–700°C, depending on conditions. Figure 7 shows the dramatic drop in steel strength at high temperature. The NIST Materials Science and Engineering Laboratory provided models of each steel's behavior at high temperature for the models of building behavior.

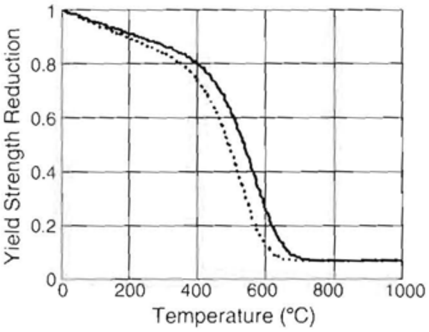

Figure 7. Reduction of yield strength of steel from the room-temperature value with increasing temperature. Solid curve is structural steel. Dotted curve is characteristic of the high-strength bolts from the towers. Building fires can give rise to steel temperatures in the 500°C–700°C range.

Furthermore, there is a time-dependent deformation of steel and other metals called "creep." When steel reaches ~500°C or higher, creep makes the steel move and change shape with time, similar to how Silly Putty stretches with time, even though there is no increase in load. Creep was found to be an important factor in the building performance in the fires, so NIST included creep behavior in the high-temperature models of steel performance.

Another piece of the puzzle was failure analysis. NIST had a huge body of photographic and video evidence, including images of the hole created by the airplane on the north face of the North Tower showing details of structural damage. The NIST team could see that columns struck by the outer parts of the wings were not severed, and that the wing structure simply broke up and sieved through the building. The heavier parts of the wings that contained the fuel easily severed the columns. With image analysis, NIST could ascertain what kind of damage was done, where the bolts broke between columns or where the steel was cut straight through. The NIST team then used these conclusions as a validation for the model of building performance during aircraft impact.

Other evidence for failure analysis included the recovered steel. Remarkably, some of the recovered pieces were in much the same shape as they were immediately after being hit by the airplane; the collapse itself did relatively minor damage to the material. One such piece was hit directly by the upper part of the fuselage. The observed damage was compared with the models of impact damage to this piece. Details of the damage, such as punching-in of the outer web plated into the center of the column, were consistent between the model of impact damage to this particular panel and the recovered steel.

This particular perimeter panel was also important because it was damaged at a high deformation rate, and steel and welds can become brittle like glass when strained at very high rates. Brittle materials absorb very little energy when fractured, and with that type of behavior, the airplane would have gone through the perimeter columns without losing much energy, doing more damage to the core. The models could only be accurate if the fracture behavior were known. In the perimeter panel, NIST investigators could see ductile fracture with substantial thinning of material during deformation, even at one of the highest strain rates involved in the impact, and there was no catastrophic loss in ductility.

Damage to the fire protection materials was another important part of the analysis. A sprayed-on fire protection material—originally asbestos, later various asbestos substitutes—had been applied to the perimeter columns, and the oblique illumination from the sun on the various faces of the buildings showed clearly where material was knocked off during impact. In addition to the expected removal in the area of direct impact, fire protection material was also knocked off on the opposite side of the buildings due to the impact and vibration on those floors. Furthermore, the investigators could see that glancing blows on the inside of the east face of the South Tower led to the loss of fireproofing. Although there was no photographic evidence of the loss of fireproofing inside the buildings, when the planes broke up and went through, almost certainly much of the insulation in the path of the airplane debris was removed.

The photographic evidence shows that after the fires had progressed for some time, some perimeter columns were no longer standing perfectly vertically. On one face in each tower, the columns started to bow in. Why were they bowing in? The floor trusses lost their fire protection due to impact debris passing through and the vibrations caused by the impact. As a result, the long trusses heated up in the fire, lost strength, and started to sag. Once they sagged enough, they exhibited a lateral force, pulling the columns inward where they were attached at the truss seats.

Probable Collapse Sequences

The North Tower was hit first, by a Boeing 767 airplane traveling at about

440 mph. Importantly, the airplane was carrying 10,000 gallons of fuel for its intended cross-country trip. Much of the plane was stopped by the building, although the landing gear, a large structure of high-strength steel, passed completely through the building, exiting the south face and taking one perimeter panel from of the south face with it. Perhaps the most important factor was the fuel, which atomized on impact. Fireballs outside the building consumed about 30% of the fuel, and the other 70% dispersed throughout the floors; some fell down the elevator shafts and ended up burning in the lobby. The fuel itself was consumed in a few minutes, but it quickly ignited flammable materials throughout the impact floors. The sprinkler system was completely compromised by the impact.

NIST's model of the airplane hitting the North Tower showed the airplane tearing out the floors at the entry point. Much of the plane immediately disintegrated, although a few large pieces such as the landing gear, the engines, and even the tail section continued mostly intact to the interior after the fuselage opened a hole through the exterior wall. Severe damage was done to the perimeter columns and to some core columns. The fuel was dispersed throughout the floors. A substantial amount came out of the building and formed fireballs.

Figure 8a summarizes the type and extent of damage to floors 93–98 in the North Tower. The fireproofing material was dislodged from a large area inside those floors, because it was never designed to withstand such an impact; without fireproofing, the steel heated up rapidly and lost strength. Also shown is the number of core columns that were severed, according to the modeling results. A notable feature of these particular floors in the North Tower was that the stairwells were clustered fairly close together. The building codes at the time of construction specified that stairwells should be spaced as far apart as practical, but "practical" was left undefined. In this case, they were fairly close together and were severed by the impact so that no one above the impact could exit through them.

The fires were worse on the south side because the consumables were bulldozed into that section. When the steel heated up, the core columns and the 60-foot floor trusses started to lose strength; they sagged and pulled in on the perimeter columns on the south face. Shortly before collapse, the columns were observed to be bowed about 40–55 inches in one area. Eventually, the columns buckled, and the buckling instability propagated completely across the south face.

Buildings are designed to hold a static gravity load; when the upper portions of the buildings gathered downward momentum, the structures below could not stop them from collapsing. Since virtually all of the force on the building at that moment was due to gravity, the building fell straight down.

The sequence for the South Tower was similar but with some significant differences. The Boeing 767 airplane that hit the South Tower was traveling significantly faster, about 540 mph, and it struck in a more destructive way—damaging the corner of the core of the building. In this case, the right engine exited the northeast corner of the building. There was a bit less fuel, and again, a substantial amount was burnt in the fireballs outside the building. The airplane broke up immediately upon entering the building, and the parts of the plane were shuttled horizontally across the floor, either banking up against the north wall or stopping in the core. Fuel was dispersed everywhere, with a substantial amount dispersed outside of the building. All of that occurred in 600 milliseconds.

Figure 8b shows the computed damage done by the airplane in the South Tower.

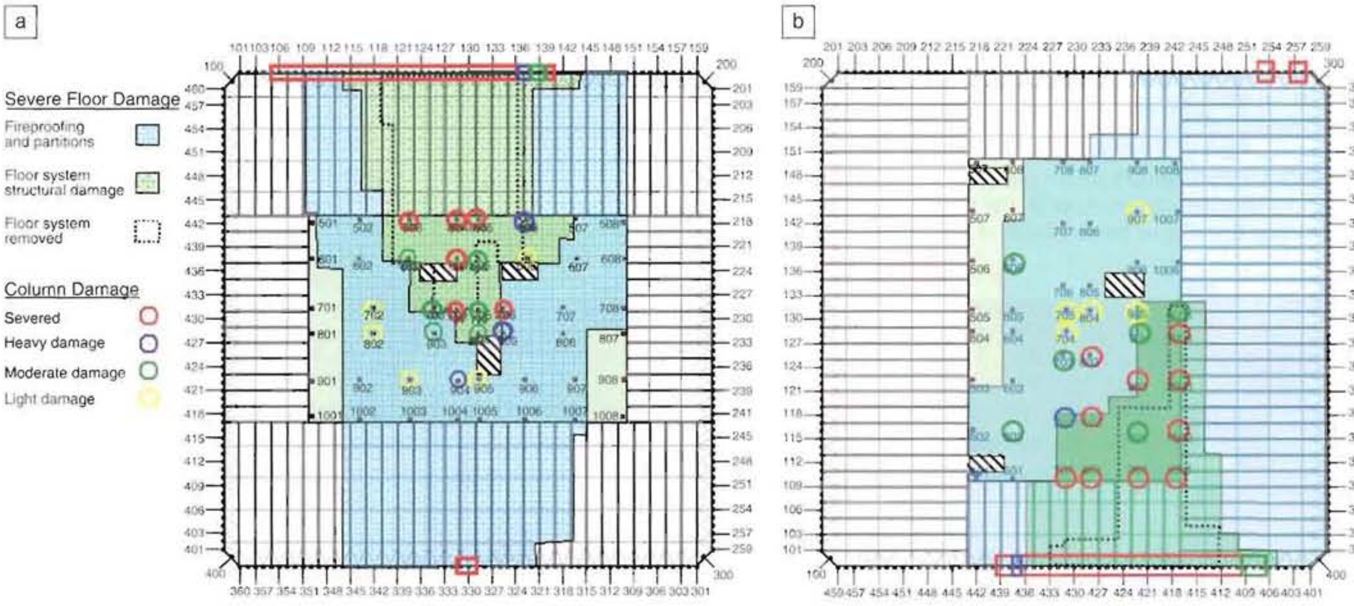

Figure 8. (a) Cumulative aircraft impact damage to floors 93 through 98 in the North Tower. Aircraft entry was from the north (top of image). The stairwells (hatched rectangles) were clustered close together in the impact floors of the North Tower, and all were impassable to occupants above the impact. Note the extended range of damage to the fireproofing; computer models indicate that if the fireproofing had remained intact, the fires would not have led to collapse of the buildings on September 11, 2001. (b) Cumulative aircraft impact damage to floors 78 through 83 in the South Tower. Aircraft entry was from the south (bottom of image). Structural damage was more severe than in the North Tower, since a massive corner column of the core of the building was severed as well as other nearby columns, making it difficult for loads to redistribute to sound columns. Note that the stairwells (hatched rectangles) were spaced far apart; the stairwell in the northwest corner of the core (upper left) was damaged but remained passable through the impact floors.

The area in blue represents the extensive damage to the fire protection. Some core columns were torn out completely and the others sustained moderate damage—and it was very asymmetric damage. The stairwells in the South Tower were well spaced at this level, and at least 18 people above the level of impact managed to get down the stairwell in the northwest corner of the core. Also, there were relatively few people left in the upper floors of the South Tower at the time of impact, since after the North Tower was struck, many had reached the lower floors using the elevators.

Much of the consumable material that fueled the fires was bulldozed toward the northeast corner. The east face supported the 60-foot floor trusses. Quicker than in the North Tower, just 18 minutes after impact, the columns were obviously bowing in, about 10 inches at this point in time. Shortly before collapse, the bowing was about 20 inches. Then, just seconds before collapse, there was a very obvious inward bowing of the columns. As in the North Tower, the columns buckled and that instability again propagated, across the east face, and the building came down.

Of the major factors that led to the collapse, it appears that the dislodging of the fireproofing from the trusses and columns was the most critical. If the fire protection had stayed on, the NIST models suggest that the buildings would have stood indefinitely. Manufacturers are currently working on developing new fireproofing materials with better adherence properties.

For More Information

A more detailed description of the factors leading to collapse are available at the Web site wtc.nist.gov. There are 42 technical reports totaling approximately 10,000 pages, plus a 248-page summary report, with recommendations, written for a more general audience.[1] We also have an overview report of the metallurgical analysis[2] and a series of articles published in the *Journal of Failure Analysis and Prevention* last October (2006).[3-7]

Acknowledgments

Special thanks go to the investigation team from the Materials Science and Engineering Laboratory, including Steve Banovic, Tim Foecke, Bill Luecke, Richard Fields, Dave McColskey, Tom Siewert, and Chris McCowan. I would also like to acknowledge the many contributions of and discussions with Fahim Sadek, Dick Gann, John Gross, and Terri McAllister of the NIST Building and Fire Research Laboratory.

Note: It is the policy of NIST to use metric units in all publications. In this and other WTC-focused documents, the inch–pound system is used whenever it was prevalent in the discipline.

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***Frank W. Gayle** is chief of the Metallurgy Division in the National Institute of Standards and Technology (NIST) Materials Science and Engineering Laboratory in Gaithersburg, Maryland. Gayle earned a DSc degree in metallurgy from the Massachusetts Institute of Technology in 1985. He also holds a BS degree in civil engineering and an MS degree in materials science from Duke University. Prior to coming to NIST, Gayle spent 11 years in industry in the field of alloy development for aerospace applications. He recently led the team of experts addressing the steel forensics aspects of NIST's investigation of the World Trade Center building performance.*

Gayle can be reached by e-mail at frank.gayle@nist.gov.