The Role of Metallurgy in the NIST Investigation of the World Trade Center Towers Collapse

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On August 21, 2002, on the direction of the U.S. Congress, the National Institute of Standards and Technology (NIST) initiated an investigation into the collapse of the World Trade Center (WTC) towers. In support of the overall investigation goals, the NIST Metallurgy and Materials Reliability Divisions pursued three objectives: assess the quality of the steel used in the construction of the towers, determine mechanical properties of the steel for input to the finite element models of the building collapse, and assess the failure mechanisms of the recovered steel components. This article describes the major findings of the metallurgical part of the NIST WTC investigation and shows how the findings were integrated into the investigation.

INTRODUCTION

Within three weeks of the collapse of the World Trade Center (WTC) towers, the Federal Emergency Management Agency (FEMA) and the American Society of Civil Engineers (ASCE) established a Building Performance Assessment Team, composed mainly of volunteers, to investigate the structural engineering and fire aspects of the collapse. This team completed and issued its report in May 2002. Congress directed the National Institute of Standards and Technology (NIST) to conduct a more in-depth analysis and on August 21, 2002, NIST initiated its investigation.

The charge to the investigation team

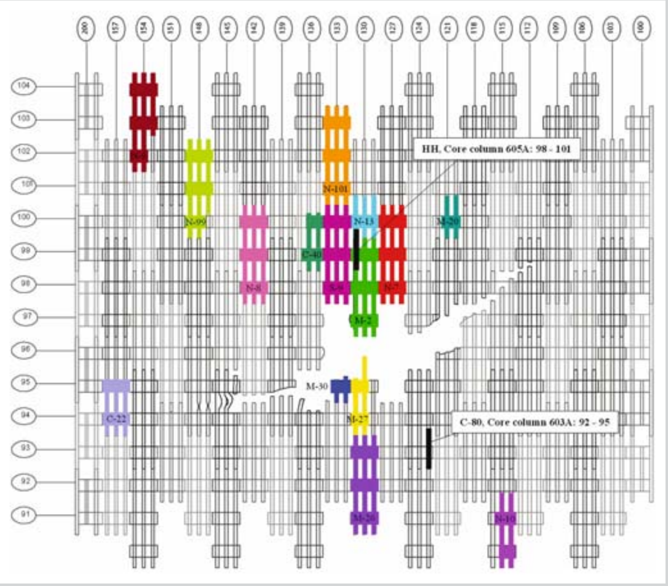


Figure 1. The locations of the recovered exterior wall columns surrounding the aircraft impact hole in WTC 1.

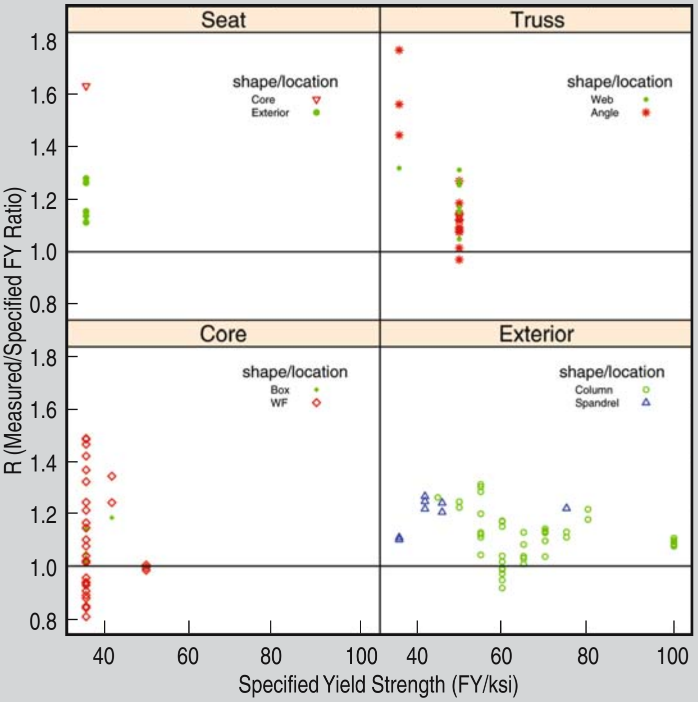


Figure 2. The ratio, R, of the measured yield strength to the specified yield as a function of specified yield strength for the 123 room-temperature tension tests.

comprised four major parts.

- "Determine why and how WTC 1 and WTC 2 collapsed following the initial impacts of the aircraft and why and how WTC 7 collapsed.
- Determine why the injuries and fatalities were high or low depending on location including all technical aspects of fire protection, occupant behavior, evacuation, and emergency response.
- Determine what procedures and practices were used in the design, construction, operation, and maintenance of WTC 1, 2, and 7.
- Identify, as specifically as possible, areas in current building and fire codes, standards, and practices that warrant revision."

The metallurgical analysis of the steel, described here, supported the modeling effort of the investigation. In support of the overall investigation goals, the NIST Metallurgy and Materials Reliability Divisions pursued three objectives: assess the quality of the steel, determine mechanical properties of the steel for input to the finite element models of the building collapse, and assess the failure mechanisms of the recovered steel components.

The body of this manuscript describes the major findings of the metallurgical part of the NIST WTC investigation and shows how the findings were integrated into the investigation. Sidebars describe the construction of the towers, the modeling of building performance, and the probable collapse sequences, which were primary outputs of the investigation.

THE METALLURGICAL INVESTIGATION

The Recovery Effort and the Structural Steel Elements

During the recovery effort after September 11, and before NIST began its collapse investigation, volunteers from FEMA, ASCE, NIST, the National Science Foundation (NSF), and the Structural Engineers Association of New York (SEAoNY) worked at the four steel recycling facilities to identify and collect steel members important to the investigation. They focused on identifying pieces that the aircraft struck or were obviously burned, as well as pieces from the fire

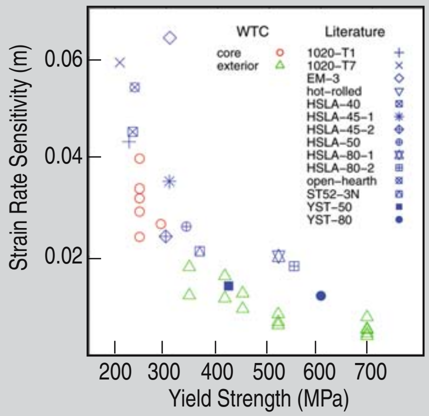


Figure 3. Strain rate sensitivities of the yield strength of core- and exterior wall-column steels compared to literature data on structural steel.

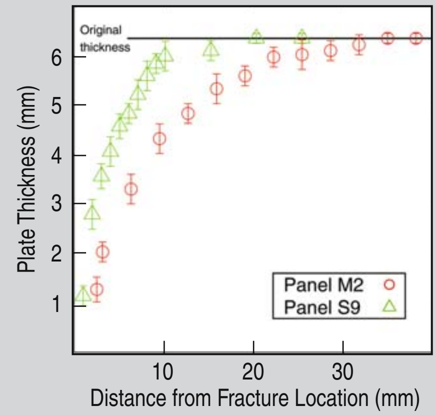


Figure 4. The thickness of exterior wall column plates near their fracture surfaces. Sections are from recovered columns M2 and S9 (see Figure 1), which were struck by the aircraft. Extensive necking demonstrates ductility even at high strain rate.

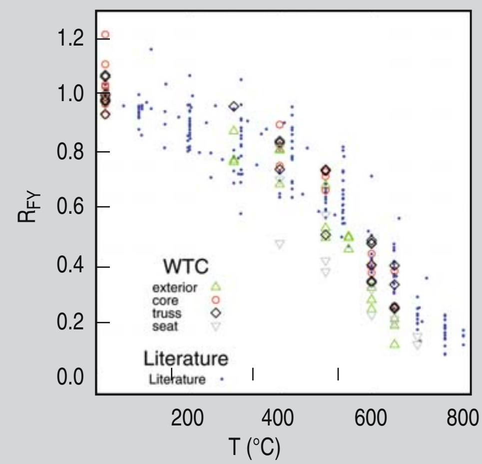


Figure 5. The high-temperature yield strength, normalized to the room-temperature value, of WTC steels compared to literature data for structural steels.

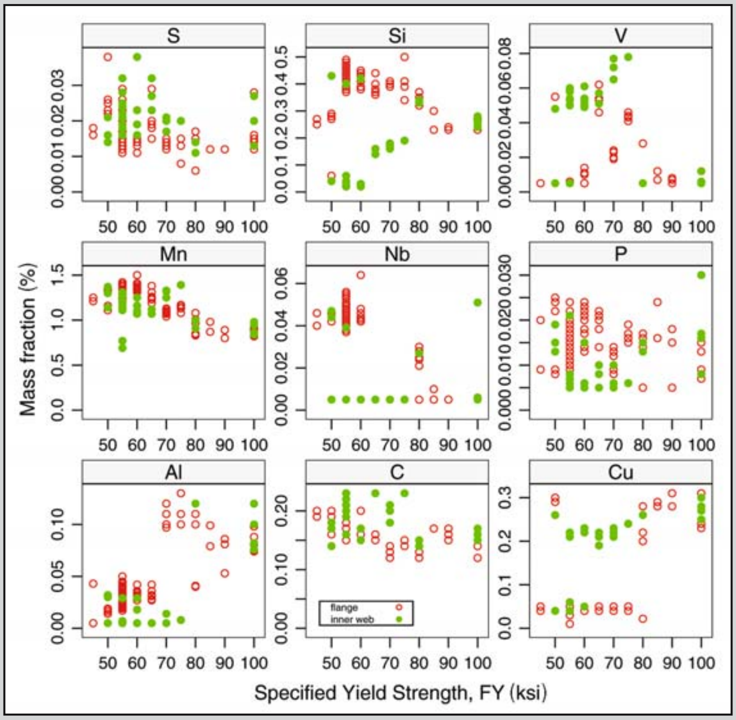


Figure 6. The chemical composition of exterior wall columns.

and impact zone. The National Institute of Standards and Technology arranged to have these pieces shipped to its facility in Gaithersburg, Maryland. The National Institute of Standards and Technology investigation team members cataloged the items and attempted to identify their original locations in the towers, using their dimensions and markings.

In all, NIST cataloged 236 structural steel elements:

- Ninety exterior column panels, of which 42 were unambiguously identified. Of those identified, 26 came from the fire and impact floors, and four of these had been struck by the airplane that hit WTC 1.
- Fifty-five core columns, of which 12 were unambiguously identified. Four of the identified columns came from the fire and impact zones.
- Twenty-three pieces of floor truss. Unfortunately, these elements had no identifying marks, so their original location in the towers is unknown.
- Twenty-five pieces of the channel that supported the floor trusses at the core; all are of unknown location.
- Forty-three miscellaneous pieces including bolts, pieces of aluminum facade, and elements from WTC 5.

Although many of the individual recovered elements are rather large, the collection represents less than 0.5 % of the more than 200,000 tons of steel used in the buildings. It does include, however, representative samples of all the relevant steels necessary for estimating properties for the impact and collapse models. Given the difficulties in locating, identifying, and safeguarding elements in the field, the extent of the collection is impressive. As an example of the coverage, Figure 1 shows the location of the recovered exterior columns surrounding the impact hole in WTC 1.

MODELING AND UNDERSTANDING THE COLLAPSE

The National Institute of Standards and Technology (NIST) Building and Fire Research Laboratory and its contractors created a complex model to understand the collapse of the towers. Three semi-independent parts comprised the model: a model of the aircraft impact and initial damage, a model of the dynamic spread of resulting fires and the thermal environment they produced, and a structural model of the resulting deformation and eventual collapse of the towers. The output of the impact and fire models fed into the structural collapse model.

The aircraft impact model enabled investigators to determine the damage to the interior of the building, which was not visible to witnesses outside, and to determine the dispersion of jet fuel. This model included about nine floors of each building and a highly detailed model of the aircraft and its fuel. It used about two million elements, employed time steps of about 1 microsecond, and modeled a fraction of the first second of the disaster. The output of the model was the structural state of the building after the impact, but before the fires began. It included estimates of the path and distribution of the debris and fuel, the areas where the spray-applied fire-resistive material was stripped from the columns and floor trusses, and estimates of the number and location of severed or damaged core columns. The aircraft impact model used material models of the deformation behavior of the structural steels, both at quasi-static and at high strain rate.

The fire model employed the NIST Fire Dynamics Simulator (FDS), a computational fluid dynamics model that numerically solves a form of the Navier–Stokes equations to model thermally driven flow. The National Institute of Standards and Technology has used FDS for forensic reconstruction of fires before the WTC investigation. The building model of the fires, which used actual tenant floor layout information, contained eight relevant floors around the impact site. Each floor was divided into a computational grid of cells approximately 0.5 m on a side. The output of the fire model was the complete thermal history of each floor, which was then used to predict the temperatures of the beams and columns.

The structural models of the two towers were used to understand the collapse hypotheses. The global model examined a base case as well as a severe damage and fire case for each tower, and took as input the state of the damaged buildings predicted by the impact model and the thermal history of the floors predicted by the fire model. The global structural model, which necessarily employed simplifying assumptions because of its computational size, was based on more detailed component models that analyzed the response of individual components, such as the floor trusses, their connections at the seats, and the shear knuckles that provided shear transfer between the concrete floor and the truss assemblies. The behavior of the exterior wall column panels was also modeled in greater detail. The results of the more detailed component models indicated which failure and deformation modes could be neglected in the global model. The structural models employed steel material models of the room and elevated-temperature stress-strain behavior, and the elevated-temperature creep behavior.

Room-Temperature Strengths and Standards

The sidebar "The Construction of the Towers" (page 26) describes the construction of the three relevant building subsystems: the exterior columns, the massive core columns, and the trusses that spanned the opening between the exterior wall and the core and supported the floors.

Because of their high strength, the steels used in the exterior wall columns are not ordinary construction steels. A typical high-rise building might use steel of only three strength grades, based on minimum yield strength (FY). In contrast, the WTC structural plans specified steels that began at a minimum yield strength FY = 36 ksi and increased from FY = 40 ksi to FY = 85 ksi in 5 ksi (34.5 MPa) increments. Corner elements in the exterior wall often used FY = 100 ksi steels. Contemporaneous construction documents indicate that the lowest strength exterior wall column steels were supplied to the ASTM A 36 standard, but all the steels with strengths above that value conformed to proprietary grades that the Port Authority of New York and New Jersey, the building owner, authorized. Yawata Iron and Steel, now Nippon Steel, supplied most of the steel plate for the exterior wall columns. The plate that faced the interior of the building usually came from a domestic mill, however.

Japanese and British mills supplied most of the steel for the core columns. These plates and hot-rolled, wide-flange shapes were mostly FY = 36 ksi ASTM A 36. Little information survived about which steel mills supplied the core beams.

The floor truss angles and webs were

specified to a mixture of ASTM A 36 and ASTM A 242. The latter is a high-strength, low-alloy (HSLA) steel, though the composition limits in the WTC construction era differ from those of the standard today. Even when the plans called for A 36, the mill often supplied an HSLA steel with substantially higher yield strength.

The investigation team characterized the room-temperature tensile behavior for examples of all relevant strength levels. Figure 2 shows the ratio, R, of the measured yield strength of the material to specified yield strength as indicated by the design drawings as a function of specified yield strength for the 123 room-temperature longitudinal tension tests conducted as part of the investigation. The tests are subdivided by the type of structural element: exterior wall columns, core columns, truss seats, and truss components. Each structural element is further subdivided into relevant components, such as truss angles and webs, exterior wall columns and spandrels, and core column plates and wide-flange (WF) shapes. Multiple specimens from each plate or shape were tested.

In general, the measured yield strengths are about 15% higher than specified. This extra strength is consistent with the results of WTC-era studies on the expected strengths of structural steel.

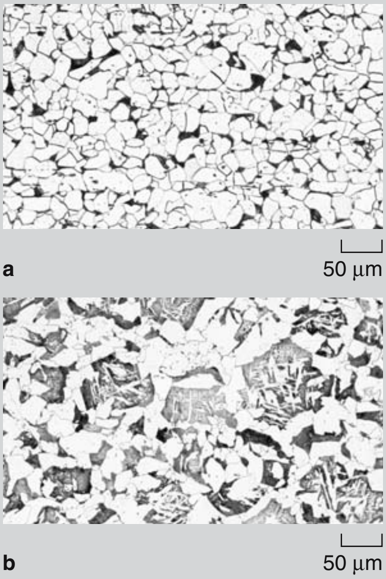


Figure 7. Optical micrographs showing ferrite morphologies. (a) Polygonal and irregular ferrite in FY = 36 ksi plate, (b) Widmanstätten ferrite in FY = 42 ksi floor truss web.

The measured strength almost always exceeds the specified strength, so that variations in processing do not produce heats that must be scrapped. Several of the tests, however, produced R < 1. The appearance of these tests that produced yield strengths less than the specified minimum cannot be interpreted as meaning that the steel was defective, however. The mill-test-report strength for a heat of steel is a quality control check. It is not a guarantee that all regions in the heat will have the minimum strength. Extensive statistical studies (Alpsten, AISI) have demonstrated that variability within the heat is small enough that the usual factor of safety in design is adequate. Furthermore, in the case of the tests of the core column steels, specimens were harvested out of necessity from deformed areas of the recovered columns. The existing deformation, calculated from the radius of curvature, was more than sufficient to remove any yield point behavior under which these A 36 steels would have been qualified. The existence of a yield point, which most of the tests of the steels with R < 1 lacked, could add up to 10% to the measured and reported strengths. The original, undeformed steels would likely have had yield strengths above the specified FY = 36 ksi.

In summary, the strengths of the recovered steels measured at NIST are consistent with the specifications under which they were delivered. The tests produced no evidence that the steels were in any way defective, and their NIST-measured chemical compositions were in almost all cases consistent with the chemical requirements of the standards under which they were delivered.

High-Strain-Rate Properties

Understanding and correctly modeling the high-strain-rate properties of the steel in the exterior wall and core columns was critical to estimating the amount of structural damage that the aircraft impact caused, which was one of the goals of the impact model. To this end, the investigation focused on the exterior wall and core columns using conventional high-rate tensile tests to estimate the strain-rate sensitivity of the strength and to examine the effect of strain rate on the ductility. The tests employed strain rates up to 500 s^{-1}, which were similar to the maximum rates predicted by the aircraft impact models. The investigation team used the experimentally measured stress-strain curves to provide a generic model of the strength as a function of strain rate to the team modeling the aircraft impact.

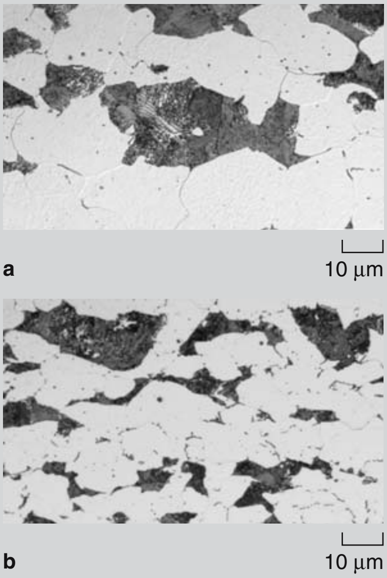


Figure 8. Optical micrographs showing pearlite morphologies. (a) Lamellar structure in FY = 45 ksi plate, (b) mottled appearance in FY = 60 ksi plate.

The measured strain rate sensitivities were similar to those of other structural steels reported in the last 25 years. Figure 3 shows the strain-rate sensitivity of the yield strength for selected exterior wall and core columns, overlaid on reported data for similar structural steels. Significantly, none of the 13 exterior wall and core column steels tested exhibited any brittle behavior, even at the highest strain rates tested. In general, the ductility increased slightly with increasing strain rate.

Macroscopically, all the exterior wall column failures due to aircraft impact that NIST examined were also ductile. In WTC 1, the aircraft severed several of the columns, often at the level of the concrete floor. Figure 4 shows that the web plates from panels struck by the aircraft (see Figure 1 for panel locations) necked over a distance of about 12 mm, reducing the plate to less than half of its original thickness due to the deformation, which indicates ductile failure. Had the failures been brittle, the exterior wall columns would have absorbed less of the impact energy; consequently more energy would have been available to damage the core columns.

In three of the four columns recovered from WTC 1 that the airplane hit, the columns split along the joints between the individual plates, specifically in the heat-affected zone (HAZ) in the web plate, but there was no evidence that the failure was due to lamellar tearing.

High-Temperature Mechanical Properties

Structural steel becomes progressively weaker with increasing temperatures above about 300°C. For temperatures up to about 500°C and the short times relevant to fires in structures, the stress-strain behavior can be treated as independent of time. At higher temperatures, time-dependent deformation, or creep, contributes to the deformation, even over these short times. Because creep deformation is generally thought of as a long-time phenomenon, it has often been neglected in fire calculations. The WTC collapse models included creep deformation of the core columns, however.

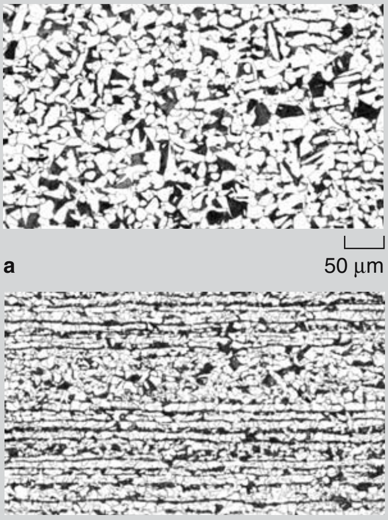
Figure 5 compares the measured 0.02% offset yield strength of the relevant recovered WTC steels to literature data on similar construction steels from both before and after the WTC construction era. The yield strengths are normalized by their room-temperature values to collapse the behavior onto a single master curve. The response of the normalized yield strength of the WTC steels is similar to the behavior of the other structural steels. It supports the commonly held rule of thumb that the yield strength at 538°C is about one-half that at room temperature.

Figure 5 reports only the yield strength, but the investigation team provided a methodology for modeling the shape of the true stress-strain curve as a function of temperature and room-temperature tensile strength for all the relevant steels.

In a parallel effort, the team characterized the creep behavior of the steels used for the floor trusses. The impact probably dislodged their fireproofing. Because their cross section was the smallest, they were the most likely to heat quickly. Based on the measured creep response of floor truss steels, the team developed a methodology for estimating the creep properties of the uncharacterized steels by scaling against the room-temperature tensile strength.

Chemistry and Microstructure

Figure 6 displays the chemistry of steels from the exterior wall columns as a function of specified yield strength. For each element, the plot is further divided by origin of the steel plate within the column. In general, the plots support the historical evidence that the inner web plate that faced the interior of the building (denoted by green, filled circles) came from a different mill than the plates



a 50 µm

b 50 µm

Figure 9. Optical micrographs showing the constituent distribution. (a) Relatively uniform distribution in FY = 36 ksi floor truss seat, (b) banded structure in FY = 65 ksi plate.

THE CONSTRUCTION OF THE TOWERS

Seven steel companies supplied structural steel to the World Trade Center (WTC) construction. Above the seventh floor, the structure of the towers comprised four main subsystems; a different steel fabricator supplied each. Pacific Car and Foundry of Seattle, Washington, fabricated the closely spaced exterior wall column panels that gave the buildings their instantly recognizable shape. Stanray Pacific of Los Angeles, California, fabricated the enormous box and wide-flange columns that made up the core. Laclede Steel of St. Louis, Missouri, fabricated the thousands of floor trusses that spanned the opening between the core and the perimeter tube. Finally, Montague-Betts of Lynchburg, Virginia, fabricated all the beams above the ninth floor.

Exterior Wall Columns

The closely spaced exterior columns formed a stiff tube that resisted all the wind loads and a portion of the gravity load. The individual columns were roughly 14 in. square, and were fabricated by welding individual plates into box columns. Three adjacent columns, each three stories high, were joined by deep, horizontal spandrel plates at every floor to form a panel. Figure A shows a three-story tall, three-column wide exterior wall panel being lifted into place, and identifies the major structural components in the exterior wall.

Once in place, the panels were bolted on the end butt plates and at splice plates that connected adjacent spandrels. Nearly every panel assembly was unique, and each was intended for a specific location on a given face of one building. In the lower floors, the individual plates that made up the perimeter columns were up to 1 in. thick, but those in the fire and impact floors of interest were typically 0.25 in. thick. Yawata Iron and Steel (now Nippon Steel) supplied most of the steel for the perimeter columns.

The design of the towers was also unusual in that the original plans called for 14 different strength grades of steel, as low as 36 ksi and as high as 100 ksi. Ordinary building construction might only use two or three strength grades. Each column in a three-column, exterior wall column panel could be fabricated from a different grade of steel as could the three spandrels. Because the wind loads differed between the different compass directions, the distribution of column strengths and thicknesses on each face of each building was unique; the two towers were not identical copies. In the floors of interest for the collapse model for WTC 1, the perimeter column plates were typically FY = 60 ksi.

Core Columns

The core of the building, which carried primarily gravity loads, was made up of a mixture of massive box columns made from three-story long plates, and heavy rolled wide-flange shapes. In general, the box columns carried the load in the lower stories, while the rolled shapes were used in the upper floors, but each type existed in the fire and impact zones. Most of the steel was specified as FY = 36 ksi. The plates for the box used in the flanges. Evidence is particularly clear for the Si, V, Nb, and Cu contents.

The plates in the exterior wall columns and the core box columns were fabricated by a "controlled rolling" process. By stringent control of the hot work processing in the austenitic state and the subsequent cooling, this process produces fine grain size and high-strength as-rolled steels that require no post processing. Using this practice, both hot-rolled (typically FY < 70 ksi) and quenched-and-tempered (FY ≥ 70 ksi) low-alloy grades were manufactured. The latter was used where a higher strength-to-weight ratio was beneficial, such as for the exterior wall columns located near the corners and upper floors of the buildings. Yawata Iron and Steel also manipulated the alloy composition to yield the specified plate properties (Figure 6), leaving the carbon content constant for nearly all steels (around 0.2% mass fraction), which is low enough for good weldability.

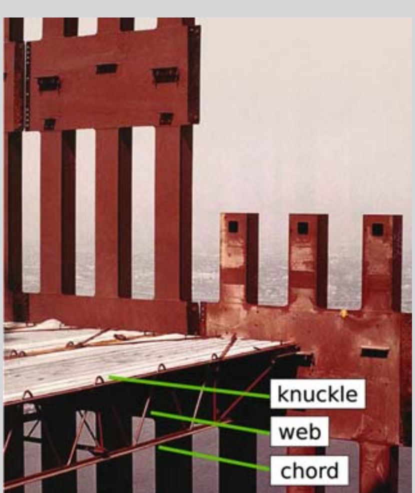
The hot-rolled steels had ferrite-pearlite microstructures with a variety of constituent morphologies. Polygonal and irregular ferrite (Figure 7a) occurred in all grades; the grain size decreased with increasing yield strength. This grain refinement was achieved primarily through microalloying with vanadium and niobium additions (see Figure 6). An intragranular acicular or Widmanstätten morphology occurred in some higher strength steels with 60 ksi ≤ FY < 70 ksi as well as in steels that contained significant vanadium additions (e.g., steels used for the floor truss components), as shown in Figure 7b. This morphology formed due to the continuous cooling practices that dictated the degree of undercooling during fabrication of the plates. Similarly, the morphology of the pearlite constituent of the hot-rolled steels varied. Pearlite colonies in lower-strength steels were large, with a dense but distinguishable lamellar structure (Figure 8a). Pearlite colonies in higher-strength steels were smaller and appeared mottled. The lamellar spacing could not be resolved using optical microscopy, and the cementite phase (Fe_3C) appeared granular at times (Figure 8b). The difference in pearlite appearance is associated with the alloy chemistry and deoxidation practices in use at the time.

Steels with low manganese content that were also aluminum-killed prefer-

columns came from Japanese mills and were fabricated on the west coast and shipped to New York. Japanese and British steel mills supplied most of the wide-flange columns and beams used above the seventh floor, which were detailed by a fabricator on the east coast.

Floor Trusses

Lightweight floor trusses supported the concrete floors that spanned the open space between the conventionally framed core and the exterior wall columns. The chords of the floor trusses were fabricated from 0.25 in. or 0.375 in. L-angles, while their webs were typically made from a single length of 0.75 in. round bar. Laclede Steel rolled the shapes from steel made in its own electric-arc furnace. It also welded the individual truss sections, and then shipped them by rail to New Jersey, where the erection company assembled them into floor panels that were lifted by crane into place. Figure A also shows a completed floor panel before the concrete floor was poured. The trusses were bolted and welded to seats on the spandrels of the exterior wall column panels. The truss seats on the opposite end at the core, not visible in Figure A, were similar. The webs projected above the level of the truss top chord and formed a knuckle to provide a composite action that tied the concrete floor to the floor trusses.



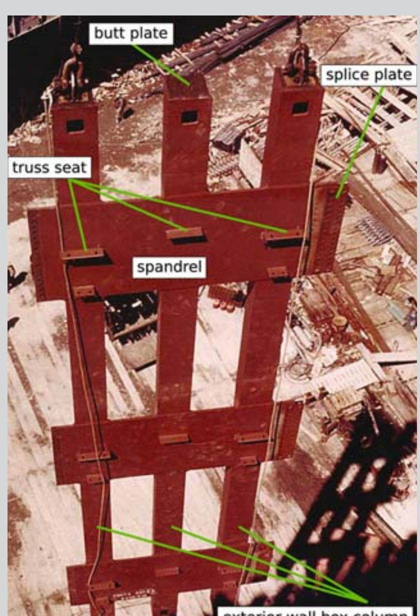


Figure A. Images of the exterior wall columns and floor truss assemblies during construction of the towers. The figure shows the major structural components and how they were assembled (Source unknown).

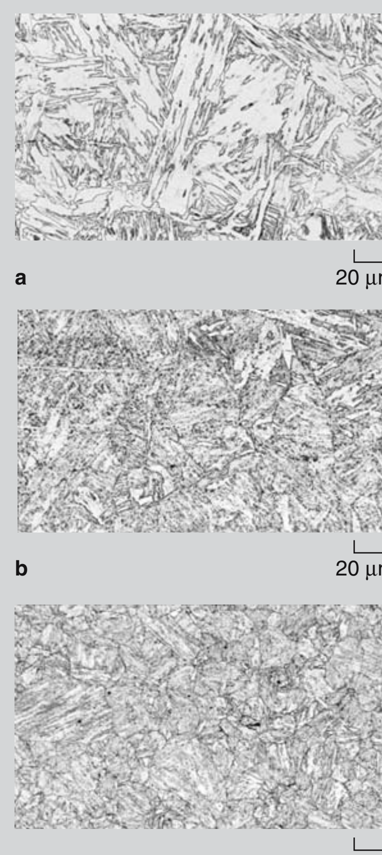


Figure 10. Optical micrographs showing structures of quench-and-tempered plates. (a) Widmanstätten or bainitic structure in FY = 70 ksi plate, (b) tempered martensite in FY = 75 ksi plate, and (c) tempered martensite in FY = 100 ksi plate.

entially form this mottled pearlite morphology. The elevated aluminum levels suggest an effort to significantly deoxidize the steel.

The spatial distribution of these microstructural constituents was frequently not uniform. In general, the ferrite and pearlite were uniformly distributed in the lower strength plates (FY < 55 ksi), floor truss components (chords and webs), and floor truss seats (Figure 9a). In contrast, ferrite and pearlite in the higher-strength plates were distributed into bands that were elongated in the rolling plane, which resulted in a laminated structure in cross section (Figure 9b). For some plates, regions near the centerline were more heavily banded than those near the surface. Constituent banding in low-carbon steels is common in hot-rolled plates and is caused by chemical segregation through the thickness of the plate. The surplus or deficiency of alloying elements in the bands determines the transformation products that form on cooling from the processing temperature.

Quench-and-tempered plates exhibited two morphologies. Ferrite grains in steels with FY = 70 ksi were shaped like broad needles or leaves and were surrounded by coarse cementite precipitates (Figure 10a). The morphology of the ferrite constituent and distribution of the cementite phase indicates either a coarse Widmanstätten or bainitic structure. Tempered martensite occurred in steels with FY ≥ 75 ksi (Figure 10b and 10c). As the strength of the plate increased, the remnants of ferrite lath boundaries became more distinct, but the carbides at the prior austenite grain and ferrite lath boundaries became less discernible. To strengthen and improve the hardenability of the plates, chromium and molybdenum were added.

CONCLUSION

Based on the metallurgical investigation of the steel recovered from the WTC collapse site, it was determined that the mechanical properties and chemistry of the steels used in the World Trade Center towers were consistent with the specifications called for in the building plans. Microstructurally, the lower-strength exterior wall and core-column steels were ferrite-pearlite control-rolled steels. Higher-strength steels in the exterior wall columns were quenched and tempered. Measured mechanical properties at high strain rates, necessary for modeling the impact of the aircraft, were similar to other ordinary construction steels. Neither high-rate tests nor recov-

THE FAILURE OF THE TOWERS

At 8:46:30 the first airplane struck the north wall of World Trade Center (WTC) 1 between floors 93 and 98. About 15% of the jet fuel burned in the fireball outside the building. Another 15% burned inside the building immediately. The rest fueled the fires that started. The overpressure from the fireball blew out many of the windows, which subsequently provided oxygen for fires. The impact damaged or severed 38 of 59 exterior columns on the north wall, and, based on the aircraft impact analysis, 9 of the 47 core columns. The passage of the impact debris through the tower stripped the insulation from columns and floor trusses on the impact floors. Over the next 102 min., the fires moved from the north (impact) side to the south side. Eighty minutes after impact, the south wall began to bow inward. At 97 min., it reached its maximum observed displacement of 1.4 m. Just before collapse, the building section above the impact zone tilted to the south, and at 10:28:25, 102 min. after impact, WTC 1 began to collapse.

The second airplane struck the south wall of WTC 2 at 9:02:59 between floors 78 and 84. The effects of the fireball were similar to those in WTC 1. The impact damaged 32 of 59 exterior wall columns, and based on the aircraft impact analysis, 11 of 47 core columns. As in WTC 1, the passage of the impact debris stripped insulation from columns and floor trusses. Unlike WTC 1, the fire moved quickly to the east side of the building, but then remained there. Within ten minutes of impact, the east wall began to bow inward. Just before collapse, the building section above the impact zone tilted to the east and south, and at 9:58:59, 56 minutes after impact, WTC 2 began to collapse.

The Most Probable Collapse Sequence

The investigation team integrated the photographic record, the eyewitness accounts, the experimental results, and the results of the aircraft impact analysis, fire spread and growth analysis, heat conduction analysis, and structural response analysis to determine the probable collapse sequence for each tower. Report *NIST NCSTAR 1-6,* from which this summary is abstracted, summarizes the observations, results, and findings in much greater detail.

The sequences of events leading to collapse initiation were similar, but not identical, for each tower. Four major structural events were common to both sequences. First, the floors that lost insulation due to debris impact sagged as the truss members deformed and buckled under elevated steel temperature. The sagging floors pulled inward at the column connections and caused the exterior wall to bow inward. Next, the exterior wall bowed and plastically buckled under the combined effects of the reduced strength at elevated temperatures, increased axial loads redistributed from the severed columns, pull-in forces from sagging floors, and loss of lateral support due to failure of truss seat connections. Then, the core columns weakened under the combined effects of structural impact damage, reduced elevated temperature strength, and plastic buckling of core columns. In addition, the loads on the remaining core columns increased as gravity loads redistributed from the damaged core columns. Finally, the gravity loads redistributed because of the impact damage, restrained thermal expansion, weakening of the core, leaning of the section above the impact damage, and bowing and buckling of exterior walls. The hat truss primarily redistributed the gravity loads from the core to the exterior walls, but the adjacent exterior walls redistributed load primarily through the spandrels.

All three major subsystems—the building core, the building floors, and the exterior walls—played a role in the structural collapse sequence for WTC 1 and WTC 2.

Role of the Building Core

The core columns were designed to carry the building gravity loads and were loaded to approximately 50% of their capacity before the aircraft impact.

The core columns were weakened significantly by thermal effects and by the aircraft impact damage. Thermal effects dominated the weakening of WTC 1. As the fires moved from the north to the south side of the core, the WTC 1 core was weakened over time by significant creep strains on its south side. Aircraft impact damage dominated the weakening of WTC 2. Immediately after impact, the vertical displacement at the southeast corner of the WTC 2 core increased 15 cm, from 10 cm to 25 cm. With the impact damage, the core subsystem leaned to the southeast and was supported by the ered components gave any evidence of brittle failure. The high-temperature mechanical properties, necessary for modeling the response to the fires, were consistent with other construction steels.

south and east floors and exterior walls.

Gravity loads redistributed from the core to the exterior faces primarily through the hat truss due to aircraft impact and thermal effects. The WTC 1 core carried 1% less load after impact but 20% less after thermal weakening. The WTC 2 core carried 6% less load after impact and 2% less load after thermal weakening.

Additional axial loads that were redistributed to the exterior columns from the core were not significant (only about 20% to 25% on average), because the exterior columns were loaded to only approximately 20% of their capacity before the aircraft impact.

Role of the Building Floors

The floors were designed to support occupancy loads and transfer them to the core and exterior columns. They were also designed to act as horizontal diaphragms when the buildings were subject to high winds.

In the collapse of the towers, the floors provided inward pull forces as they sagged significantly under thermal loads. However, the sagging floors continued to support their floor loads despite the dislodged insulation and extensive fires. Some truss seat connections with dislodged insulation at the exterior columns did fail and disconnect from the exterior wall under thermal loads. Floor disconnections increased the unsupported length of the exterior columns and distributed floor loads to adjacent truss seats. No inward pull forces existed where the floors were disconnected.

Role of Exterior Walls

Column instability over an extended region of the exterior face ultimately triggered the global system collapse, because the loads could not be redistributed through the hat truss to the already weakened building core. In the area of exterior column buckling, loads transferred through the spandrels to adjacent columns and adjacent exterior walls. As the exterior wall buckled, on the south face of WTC 1 and the east face of WTC 2, column instability propagated to adjacent faces and caused the initiation of the building collapse.

The exterior wall instability was induced by a combination of thermal weakening of the columns, inward pull forces from sagging floors, and to a much lesser degree, additional axial loads redistributed from the core.

Conclusions of the Analysis

Floor sagging and inward bowing of an exterior wall were necessary but not sufficient conditions to initiate collapse. In both WTC 1 and WTC 2, significant weakening of the core due to aircraft impact damage and thermal effects was also necessary. The National Institute of Standards and Technology considered the observed performance, evidence, and analysis results for each tower, and reached two conclusions. First, in the absence of structural and insulation damage, a conventional fire substantially similar to or less intense than the fires encountered on September 11, 2001 likely would not have led to the collapse of a WTC tower. Second, the towers likely would not have collapsed under the combined effects of aircraft impact and the subsequent multi-floor fires encountered on September 11, 2001 if the insulation had not been widely dislodged or had been only minimally dislodged by aircraft impact.

The existing thermal insulation, had it not been stripped off in the impact, would have been sufficient to keep the steel temperatures low enough to minimize deformation. Also, the investigation team neither found nor invoked any extraordinary events, beyond the terrorist attack that damaged the structure and removed the insulation, that led to the collapse of the towers.

The difference in the time it took for each WTC tower to collapse was due primarily to the differences in structural damage, the time it took the fires to travel from the impact area across the floors and core to critical locations, and the time it took to weaken the core and exterior columns. The structural damage to the WTC 2 core was asymmetric, including a corner core column that was severed. The damage to WTC 1 was more symmetrical; it was located in the center portion of the core and extended from the north side to the south side. The fires in WTC 2 reached the east side of the building more quickly (within 10 to 20 minutes) than the 50 to 60 minutes it took for the fires in WTC 1 to reach the south side.

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