THE STRUCTURAL STEEL OF THE

# WORLD TRADE CENTER TOWERS

Fig. 1 — The World Trade Center in New York City before the terrorist attack. Image courtesy Port Authority of New York and New Jersey.


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In September 2002, the National Institute of Standards and Technology became the lead agency in the investigation of the World Trade Center (WTC) terrorist attacks of September 11, 2001. The investigation addresses many aspects of the building collapse, from occupant egress to factors affecting how long the towers stood after being hit by the airplanes, with the goal of gaining valuable information for the future. The complete plan for the NIST investigation is available at <*http://wtc.nist.gov*>.

A major part of the investigation is the metallurgical analysis of structural steel from the World Trade Center *(Fig. 1).* The analysis includes characterization of mechanical properties, failure modes, and temperature excursions endured by the steel. This overview on the metallurgical investigation describes the structure of the towers, steel recovered from the site, and special issues faced in the analysis of the steel.

**Design of the WTC towers**

The 110-story WTC towers were constructed by a novel tube technology. The core was a conventionally framed structure, albeit with massive columns, which carried only gravity loads. The perimeter of the building, which resisted the wind loads as well as carrying part of the weight of the building, was assembled from closely spaced 14 x 14 inch box columns that gave the building its characteristic exterior. Figure 2 shows a prefabricated perimeter column panel being hoisted into place.

Once in place, the columns were bolted to the columns below, and the deep spandrels were bolted together side-to-side using splice plates. Inside the building, each individual floor enclosed an acre of wall-free, open space. Lightweight floor trusses, also visible in Figure 1, spanned the open space between the core and perimeter columns in a two-dimensional lattice, and supported a four-inch thick lightweight concrete floor. At the core and perimeter, truss seats supported the floor trusses.

Because of the enormous size of the construction job, many different companies provided structural elements for the buildings. Four different fabricators were responsible for the fire and impact zones relevant to the NIST investigation.

• The perimeter panel sections were fabricated on the West Coast and shipped to a staging area

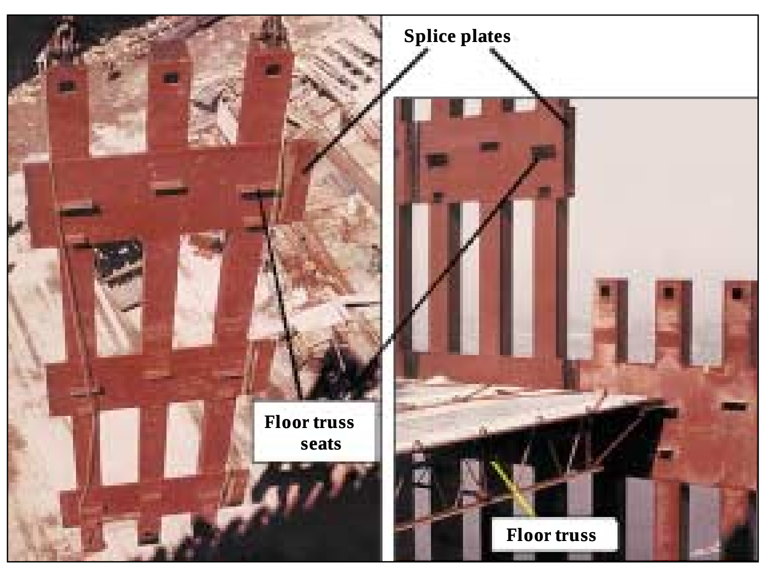


Fig. 2 — A three-column perimeter panel being lifted into place (left). Arrangement of perimeter panels and floor trusses connecting the perimeter columns and the tower core structure (right). Source unknown.

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*Fig. 3 — Enhanced photographs used to determine pre-collapse damage to the perimeter panels of WTC 1. Colored boxes indicate location of recovered panels that were damaged as a result of aircraft impact.*

in New Jersey before assembly in Manhattan. Pacific Car and Foundry of Seattle fabricated these three-column assemblies, primarily using steel from Yawata Iron and Steel (now Nippon Steel). Domestic steel (less than 10% by weight) was also used for some of the plates on inner side of the column. The structural engineering plans called for fourteen different yield strengths of steel in the perimeter columns, of which twelve were actually used.

• The core of the buildings consisted of two different types of columns, fabricated by different contractors.

• Stanray Pacific of Los Angeles fabricated the massive welded box columns from plates up to seven inches thick. The steel for these columns came almost exclusively from Japanese and British mills. These massive box columns were more common in the lower stories of both towers, with a transition to rolled wide flange columns in the upper stories.

Because the airplane impact in WTC 2 was in the transition area, about half of the core columns in floors of interest were the welded box variety. In WTC 1, with a higher impact location, the core columns were primarily rolled wide-flange shapes. Montague-Betts of Roanoke, Virginia, fabricated these rolled shapes for the beams and columns in the core. The columns, many of which were the largest standard size available, also came primarily from Yawata Iron and Steel. Most of the core columns were specified to meet the standard construction steel ASTM A36, with a yield strength of 36 ksi.

• Laclede Steel of St. Louis fabricated the thousands of floor trusses from steel made in electric arc furnaces at their mill. The individual elements of the floor trusses were specified as a mixture of A36 and the higher strength ($F_y$ = 50 ksi) A242 steel. Although different components were specified as different steels, NIST has found that generally the higher strength steel was used in place of the specified A36.

### Recovery/ cataloging of steel

Beginning in October 2001, the Building Performance Assessment Team (BPAT, led by the Federal Emergency Management Agency and the American Society of Civil Engineers) and members of the Structural Engineers Association of New York (SEAoNY), began work to identify and collect WTC structural steel. They collected these pieces from the various recovery yards where debris was taken during the cleanup. NIST joined the recovery effort and provided a location for safe storage of the steel for later forensic investigation.

A major task for the NIST investigation was cataloging the recovered structural steel elements (perimeter panels, core columns, floor trusses, bolts, etc.) for further evaluation and / or testing relative to the fire and structural response of the buildings. NIST has cataloged these 236 elements, mostly from WTC 1 and WTC 2, which represent approximately 0.25% to 0.5% of the 200,000 tons of steel in the two towers.

Critical to this task was the determination of the original, as-built location of the recovered elements within the buildings. The buildings were complex, with the 14 specified grades of steel ranging from 36 ksi to 100 ksi minimum yield strength. In order to keep track of the material during construction, each piece was given a serial number indicating the location in the building. The numbers were embossed by stampings and / or painted stencils.

In many cases, the serial numbers, or at least a partial identifier, survived the collapse and subsequent recovery events. After correlating the identifiers with the structural plans for the buildings, 41 distinct perimeter panel sections were unambiguously identified from the two towers, and the location of 12 core columns was established. The following pieces of special interest were found:

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• Optimized Welds in HPS 70W and 100W Steels
• Effect of Steel Composition on the Laser Cutting Behavior of 25 mm Thick Plates
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***Session 2: Microalloying/TMCP***
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• Tailor-Made Heavy Plate Production by TMCP and Closely Related Processes
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• Steel Plates for Shipbuilding Without Conventional Heat-Treatment
• Effect of In-Line Cooling on the Properties of Hot-Rolled and Quenched-and-Tempered Microalloyed Steel
• Sour service line-pipe steel — Comparison of "low manganese steel" with conventional alloy design

**WTC1:**
- Four perimeter panels directly hit by the airplane
- 22 perimeter panels from critical floors (91 to 101)
- Two core columns from the fire-affected floors

**WTC 2:**
- Four perimeter panels from near the impact floors, and
- Two core columns from the impact floors with possible impact damage.

Additionally, floor truss material and pieces of channel that connected the floor trusses to the core columns were recovered; however, the as-built location of these structural elements within the buildings could not be identified.

Based on the markings, all identified perimeter and core columns were found to correlate one-to-one with the minimum yield strength specified by the design drawings, with the exception that 100 ksi steel was substituted for all specified 85 ksi and 90 ksi plate. The recovered structural elements provided representative samples of the 12 grades of perimeter panel material actually used, two grades of core column material (representing 99 %, by total number, of the columns), and both grades of the floor truss material.

## Failure analysis

Documentation of damage features and failure modes of the structural steel components plays an important role in

- ascertaining the structural response of the buildings, and the materials of construction, upon the impact of the plane,
- estimating the extent of internal damage,
- yielding insights into the structural integrity of the towers leading up to collapse, and
- aiding in the determination of possible mechanism(s) responsible for the collapse of each tower.

This aspect of the investigation was separated into two sections:

- Pre-collapse analysis concentrating on impact damage sustained by the exterior panel sections, based upon photographic and video images, and
- Damage characteristics of the recovered structural steel elements. Of particular importance were the samples located near the airplane impact region on the north face of WTC 1 and the south face of WTC 2, and in those areas where fire was known to be present.

Extensive image processing was used on photographs received from news organizations and the public to determine pre-collapse damage to the perimeter panels. Figure 3 shows the impact image used to extract perimeter column failure mode information from WTC 1. Superimposed onto this figure is the outline of the aircraft (Fig. 4). Careful examination of such images has allowed the characterization of the types of column failures as indicated.

Comparisons were made between such observed pre-collapse damage and the present condition of the four recovered panels that were hit. This analysis indicated that two of the impact-damaged panels are in a condition similar to that before the collapse. Some of the extraneous damage can be attributed to the events during and after collapse, but the general shape and appearance of the recovered pieces correspond well with the damage photographs. With this type of knowledge, the response of the materials can be ascertained with respect to the impact of the planes, and the ability of the airplane impact models to reproduce the event can be validated.

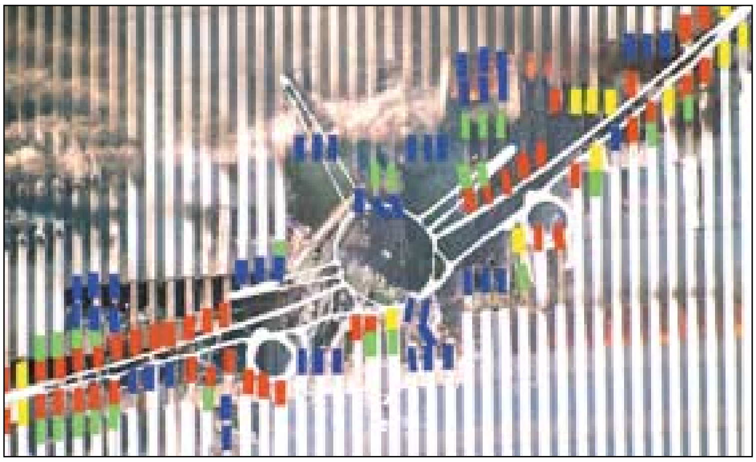

*Fig. 4 — Outline of airplane overlaid on impact damage with indications of location and type of localized damage. Red boxes indicate cut metal components, blue boxes indicate broken vertical column connection bolts, green boxes show the failure of longitudinal welds in the box columns, and yellow shows areas of indeterminate damage.*

## Mechanical properties

Recovered steel was tested to determine whether it met the required minimum properties and to provide data for models of the airplane impact and the resulting fires. Mechanical property tests indicate that all the steels likely met all required minimum test requirements.

In addition to room-temperature properties, data were generated on the effects of high temperature on the mechanical properties of the steels and on the effects of high strain rates on the mechanical properties of the steels.

Steel properties are sensitive to strain rate, and can exhibit significantly enhanced strength at high strain rates with important effects on building response to impact. A higher strength of a column should lead to increased energy absorption and reduction in momentum of the aircraft after impact, thereby reducing further damage done to the interior of the building. As expected, the yield and ultimate strengths increase with increasing strain rate. Baseline, high temperature, and high strain rate properties have been supplied to the modeling efforts of the NIST investigation. ■

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