Federal Building and Fire Safety Investigation of the World Trade Center Disaster

Project #3: Analysis of Structural Steel

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Materials Science and Engineering Laboratory
Recovered WTC steel will be characterized to:

Compare tested properties to specified yield strengths (and by location)

Assess quality of the recovered steel

Provide properties to be used in analysis of the buildings to:

- deduce the baseline performance of the buildings under wind and gravity loads
- determine how much damage was done to the buildings, especially the floors and core, by plane impacts
- determine how the steel responded to the high temperatures of the fires
- determine the most probable structural collapse sequence
3. Analysis of Steel & Specs

4. Thermal & Tenability Environment

5. Structural Collapse

Model: Building → Aircraft Impact Damage → Fires → Collapse
Tasks

- Task 1 - Collect and catalog physical evidence
- Task 2 - Document failure mechanisms and damage
- Task 3 - Metallurgical and mechanical properties determination (room temperature, high temperature, high strain rate)
- Task 4 - Correlate specified properties with measured properties
- Task 5 - Characterize thermal excursions of steel
- Task 6 – Final report
Task 1 - Collect and catalog physical evidence

- Structural steel
- Design specifications
  - sections & minimum yield strengths
  - documents from:
    - Port Authority of New York and New Jersey
    - Leslie E. Robertson Associates
- Material specifications (ASTM, etc)
- Supplier production information
  - Yawata Steel (now Nippon Steel)
  - Laclede Steel
  - Many others
WTC Tower Design

110 stories

Exterior Framed-Tube
Central Core Box Columns
Floor Slab

59 columns per side

Technical Services
Skylobby
Technical Services
Technical Services
Skylobby
Technical Services
Express Elevators
Local Elevators
Express Elevators
Local Elevators

Bar Joist
Concrete Slab
Trough decking
Electric Duct
Air-conditioning Duct

Plaza Level

Local Elevators
Local Elevators

Floor Covering

Electronic Duct
Wind loads primary factor in perimeter column design.

- 14 different grades of steel
  (36 to 100 ksi yield strength)
- Arrangement of steel neither symmetric nor the same for the two towers

Gravity loads primary factor in core column design.

- 4 grades of steel
  (99% are 36 and 42 ksi yield strength)
- Conventional (albeit massive!) column & beam construction

Simulated distribution of perimeter column yield strengths
Core Columns
Transition floors from welded box column to wide flange columns
Columns and orientations shown for 84th floor
Steel Search, Collection, Logging and Shipping to NIST

SEAoNY – Dave Sharp, many others
NIST – John Gross (NIST- BFRL)
   Dave McColskey (Matls Rel.)
   Steve Banovic (Metallurgy)

~ 1.5 million tons of debris
1/4-1/3 steel
Salvaged Steel at NIST
DOCUMENTATION OF SAMPLE REMOVAL

1. Generic diagram
2. Sample identification code
3. Removal method that causes minimal disturbance to the surrounding material

Confidential and Pre-Decisional Document

A 130: 93-96 (stenciled or stamped)

Documentation extremely important!
<table>
<thead>
<tr>
<th>236</th>
<th>TOTAL PIECES</th>
</tr>
</thead>
<tbody>
<tr>
<td>93</td>
<td>Perimeter panel sections</td>
</tr>
<tr>
<td>11</td>
<td>Box beams / Core Columns</td>
</tr>
<tr>
<td>43</td>
<td>Wide Flange sections (WF)</td>
</tr>
<tr>
<td>23</td>
<td>Trusses</td>
</tr>
<tr>
<td>25</td>
<td>Channels</td>
</tr>
<tr>
<td>2</td>
<td>&quot;Bowtie&quot; pieces of exterior wall</td>
</tr>
<tr>
<td>7</td>
<td>Coupons from Bldg 5</td>
</tr>
<tr>
<td>32</td>
<td>Miscellaneous (bolts, other)</td>
</tr>
</tbody>
</table>
Catalog of Steel – *identified perimeter panels*

41 panels identified by serial number, other markings, or geometry

- Columns – all strengths from 50 to 100 ksi
- Spandrels – all strengths from 36 to 70 ksi & 80 ksi

➢ *samples of all 14 grades specified in structural steel drawings are available for test*

**WTC 1**
- 25 panels
- 21 near impact floors
  - 3 hit directly by plane

**WTC 2**
- 16 panels
- 4 near impact floors
Catalog of Steel – identified core columns

**WTC 1**
- 8 columns
  - 5 wide flange
  - 3 built-up box columns
- 1 from impact zone

**WTC 2**
- 5 columns
  - 2 wide flange
  - 3 built-up box columns
- 2 from impact zone

- samples are available of 2 grades (36 and 42 ksi) of both box and wide flange columns, configurations which represent 99% of core columns in the towers.
North Tower
North Face

Identified perimeter panels

Sections Identified as of May 5, 2003

As determined by the NIST Metallurgy Division

Core column, 603
Specifications and Steel Supplier Documents

- Port Authority contracts – allowable steels
  - ASTM steel designations
  - certain proprietary steel

- Structural Steel design drawings
  - provide minimum yield strength for all steel components

- ASTM specifications for individual steel types
  - composition
  - mechanical properties (room temperature only)

- Supplier production information
  - grade substitutions (always to higher strength)
  - typical properties for proprietary steels
  - Laclede Steel and Nippon Steel (Yawata) extremely helpful

Analysis of these documents allow estimation of typical properties when specified minimum yield strength is known.
Truss Properties – Laclede Steel
Supplier of approximately 50 truss variants of 60', 35', and bridging trusses

- Supplier documents show where substitutions were made

Specified properties for 60’ truss

- **Top Chord**
  - A 242  (50 ksi minimum Yield Strength)

- **Web**
  - A 36  (36 ksi minimum Yield Strength)

- **Bottom Chord**
  - A 36 specified
    - (but mostly higher strength A 242 supplied instead)
## Estimated Properties - Perimeter Columns

### Pacific Car & Foundry
Seattle, WA
55 800 tons, 36 ksi – 100 ksi

**Plate 1,2: Yawata**
- Exterior wall column plates 1, 2, 4
- 42 57 (1,3) Yawata "A 441 mod"
- 45 57 (3) Yawata "A 441 mod"
- 50 58 Yawata "A 441 mod"
- 55 65 for plates with t<=1.5" Yawata "A 441 mod"
- 55 66 for plates with t> 1.5" Yawata WEL-TEN 60
- 60 70 for plates with t<=1.25" Yawata "A 441 mod"
- 60 71 for plates with t>1.25" Yawata WEL-TEN 60
- 65 76 for plates with t>0.5" Yawata WEL-TEN 60
- 65 76 for plates with t<=0.5" Yawata WEL-TEN 60R
- 70 81 Yawata WEL-TEN 62
- 75 86 Yawata WEL-TEN 62
- 80 91 Yawata WEL-TEN 70
- 90 105 (2) Yawata "A 514 mod" (WEL-TEN 80C)
- 100 105 Yawata "A 514 mod" (WEL-TEN 80C)

*Actual yield strength estimated by NIST based on supplier documents.*
Task 2  Document Failure Mechanisms and Damage

• Analysis in progress
• Examination of local damage and failure mechanisms
• Requires deciphering of post-collapse damage from pre-collapse
  • image analysis, comparison of pre-collapse images with salvaged steel
• Wiss, Janney, Elstner contractors
  • Experts in structural failure analysis
  • Will provide observations and statistics of repeated patterns of post-impact failures/fractures of bolts, welds, truss seats, spandrel splices, and column splices, & fire damage described as function of location (in or away from impact zone or fires)
  • Identify any structural elements that might have been especially sensitive to the fire
• These observations will help us estimate energy absorbed during impact, and performance in fire.
Task 3 – Mechanical Property Determination

- **Room Temperature Tensile**
  - Analysis of baseline structural performance
  - Comparison with specified properties

- **High Strain Rate**
  - Analysis of aircraft impact damage
  - Analysis of most probably structural collapse sequence

- **High Temperature**
  - Analysis of structural response to fires
  - Analysis of most probable structural collapse sequence
Room Temperature Mechanical Properties

**NIST Tensile tests**
- Yield and ultimate strength, ductility and workhardening behavior (per ASTM A370 and E8)
- for comparison with specified properties
- for analyzing baseline structural performance

**Specimens**
- perimeter columns (12 +) and spandrels (10)
- core box columns (2) and wide flange columns (2)
- truss components (3 +) and inner & outer seats (2 +)
- channels, splice plates, welds, bolts
Mechanical properties

Measured yield strength vs specified minimum yield strength

Note: Specified minimum values apply to plate tested at the mill, not steel product
Measured Truss Properties

Tested at NIST from truss specimens recovered from WTC. Location in building unknown

**Chemistry**

<table>
<thead>
<tr>
<th>Element</th>
<th>A36 angle</th>
<th>A242 Angle</th>
<th>A242 round</th>
</tr>
</thead>
<tbody>
<tr>
<td>C (wt %)</td>
<td>0.20</td>
<td>0.18</td>
<td>0.21</td>
</tr>
<tr>
<td>Mn</td>
<td>0.77</td>
<td>0.86</td>
<td>0.79</td>
</tr>
<tr>
<td>P</td>
<td>0.009</td>
<td>0.016</td>
<td>0.008</td>
</tr>
<tr>
<td>S</td>
<td>0.032</td>
<td>0.028</td>
<td>0.019</td>
</tr>
<tr>
<td>Cu</td>
<td>0.26</td>
<td>0.29</td>
<td>0.08</td>
</tr>
<tr>
<td>V</td>
<td>0.036</td>
<td>0.044</td>
<td>0.038</td>
</tr>
<tr>
<td>N</td>
<td>0.008</td>
<td>0.0066</td>
<td>0.008</td>
</tr>
</tbody>
</table>

**Mechanical Properties**

<table>
<thead>
<tr>
<th></th>
<th>FY (ksi)</th>
<th>UTS (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>57.6</td>
<td>78.3</td>
</tr>
<tr>
<td></td>
<td>60.3</td>
<td>76.6</td>
</tr>
<tr>
<td></td>
<td>60.0</td>
<td>80.5</td>
</tr>
</tbody>
</table>

Elongations acceptable

**Observations**

* A36 components far exceed minimums.

* No substantial differences (chemistry/microstructure/mechanical) between steel specified as A 36 and A 242

* Truss steel would meet present day A 572 (50 ksi minimum yield strength)
High Strain Rate Mechanical Properties

**NIST High Strain Rate tests**

- High strain rates cause significant increase in strength of steel
- Higher strength and energy absorption slow aircraft to greater extent
- Accurate modeling must account for the associated decrease in damage to internal structure
- Aircraft impact lead to strain rates estimated at 100 to 1000 per second

**Specimens**

- perimeter columns and spandrels
- core box columns and wide flange columns
- bolts
High Strain Rate Mechanical Properties

**Conventional tensile vs Kolsky Bar (compression)**

**HSR tensile tests**
- Yield and ultimate strength, ductility and workhardening behavior
- Strain rates up to 500 per second (50,000% elongation per second)

**HSR compression tests**
- Yield strength and workhardening behavior
- Strain rates from 500 per second to 5000 per second (500,000% elongation per second)
- Specialized Kolsky Bar equipment at NIST
### High Strain Rate Test Matrix

Grades of steel (duplicates) tested at each condition

<table>
<thead>
<tr>
<th>Tensile test</th>
<th>Strain rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 s⁻¹</td>
</tr>
<tr>
<td>Outer Columns</td>
<td>10</td>
</tr>
<tr>
<td>Spandrels</td>
<td>2</td>
</tr>
<tr>
<td>Core columns</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Compression</th>
<th>500 s⁻¹</th>
<th>700 s⁻¹</th>
<th>900 s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Columns</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Spandrels</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Core columns</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Bolts</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
High Strain Rate Test Data

![High Strain Rate Test Data Graph](image-url)
Elevated Temperature Properties

- The fires did not melt the steel structure
- Steel loses strength and modulus (stiffness) at temperatures typical in a fire

• **Hot Tensile Tests**
  - Yield, ultimate, ductility, workhardening
  - 400, 500, 600, 650 ºC
  - Strain rate is critical
  - Provides guidance for creep tests

• **Creep**
  - “run-away strain” in A36 occurs 100 ºC lower if creep effects included in standard fire
  - 400, 500, 600, 650 ºC @ 2 stress levels
  - constant load, measure strain vs. time
  - creep ductility

• **Elastic Modulus** (buckling concerns)
High Temperature Tensile Test Results
Truss Properties

![Graph showing the relationship between temperature (°C) and stress (MPa) for different temperature ranges. The graph includes curves for yield strength and ultimate tensile strength. There is a note indicating "Truss – upper chord."](image-url)
High Temperature Creep

Deformation under constant load

Testing under way for:
Core columns
Perimeter columns
Floor truss

Figure 11. Measured and predicted strains during a non-linear heating rate for stresses of 1/3 and 2/3 of the room temperature yield strength.
High Temperature – Elastic Modulus (stiffness)

Young's Modulus

Equation based on NIST measurements and other steel data

Range of NIST measurements on WTC steels

Temperature, °C

Modulus, GPa
## Current Status of Mechanical Test Program

<table>
<thead>
<tr>
<th>Test Description</th>
<th>% Complete</th>
<th>Est. Completion Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT tensile tests (quasistatic)</td>
<td>95%</td>
<td>9/03</td>
</tr>
<tr>
<td>High temperature tensile tests</td>
<td>40%</td>
<td>10/03</td>
</tr>
<tr>
<td>Creep</td>
<td>10%</td>
<td>12/03</td>
</tr>
<tr>
<td>High Strain Rate (tensile)</td>
<td>75%</td>
<td>10/03</td>
</tr>
<tr>
<td>High Strain Rate (compression)</td>
<td>50%</td>
<td>10/03</td>
</tr>
<tr>
<td>Welds</td>
<td>30%</td>
<td>12/03</td>
</tr>
<tr>
<td>Bolts (tensile &amp; High Strain Rate)</td>
<td>75%</td>
<td>9/03</td>
</tr>
</tbody>
</table>
Finally,

The Materials Science and Engineering Laboratory is proud to contribute its knowledge and expertise to the investigation.

Comments are welcome on:

• Goals and scope of test program
• Test methods
• Analysis of data
• Other areas of interest