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

Project #3: Analysis of Structural Steel

Update

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NIST

Project 3 Tasks

- Task 1 - Collect and catalog physical evidence
- Task 2 - Document failure mechanisms and damage
- Task 3 - Determine metallurgical and mechanical properties (room temperature, high temperature, high strain rate)
- Task 4 - Correlate specified properties with measured properties *(combined with Task 3)*
- Task 5 - Characterize thermal excursions of steel
- Task 6 - Prepare final report

Task 1 - Collect and catalog physical evidence – (complete)

- Structural steel
  - *236 items catalogued; all relevant steels in inventory*
- Design specifications
  - *relevant structural documents reviewed*
  - *identified upgrades and material substitutions*
- Material specifications (ASTM, foreign specs, etc.)
- Supplier production information
  - *Supplier documents, other 1960's era documents used to estimate properties*
  - *Changes identified in test methods*

- *Two reports issued:*
  - *WTC Steel Inventory and Identification within Buildings*
  - *Contemporaneous Structural Steel Specifications*

Task 2 - Document failure mechanisms and damage (complete)

- Contractor visual inspection of steel and analysis of failures completed; report drafted
- Extensive analysis by NIST of steel
  - failure mechanisms analyzed and documented
  - repeated patterns of fracture/failure analyzed
  - failures mapped on structure
- Photographic evidence enhanced and compared with recovered steel.
  - many recovered panels not significantly damaged by collapse
  - allows better understanding of fracture and energy absorption

➢ *Report being drafted*


WTC 2
South Face
(original image)
© 2001 Chris Sorensen


WTC 2
South Face
(enhanced image)
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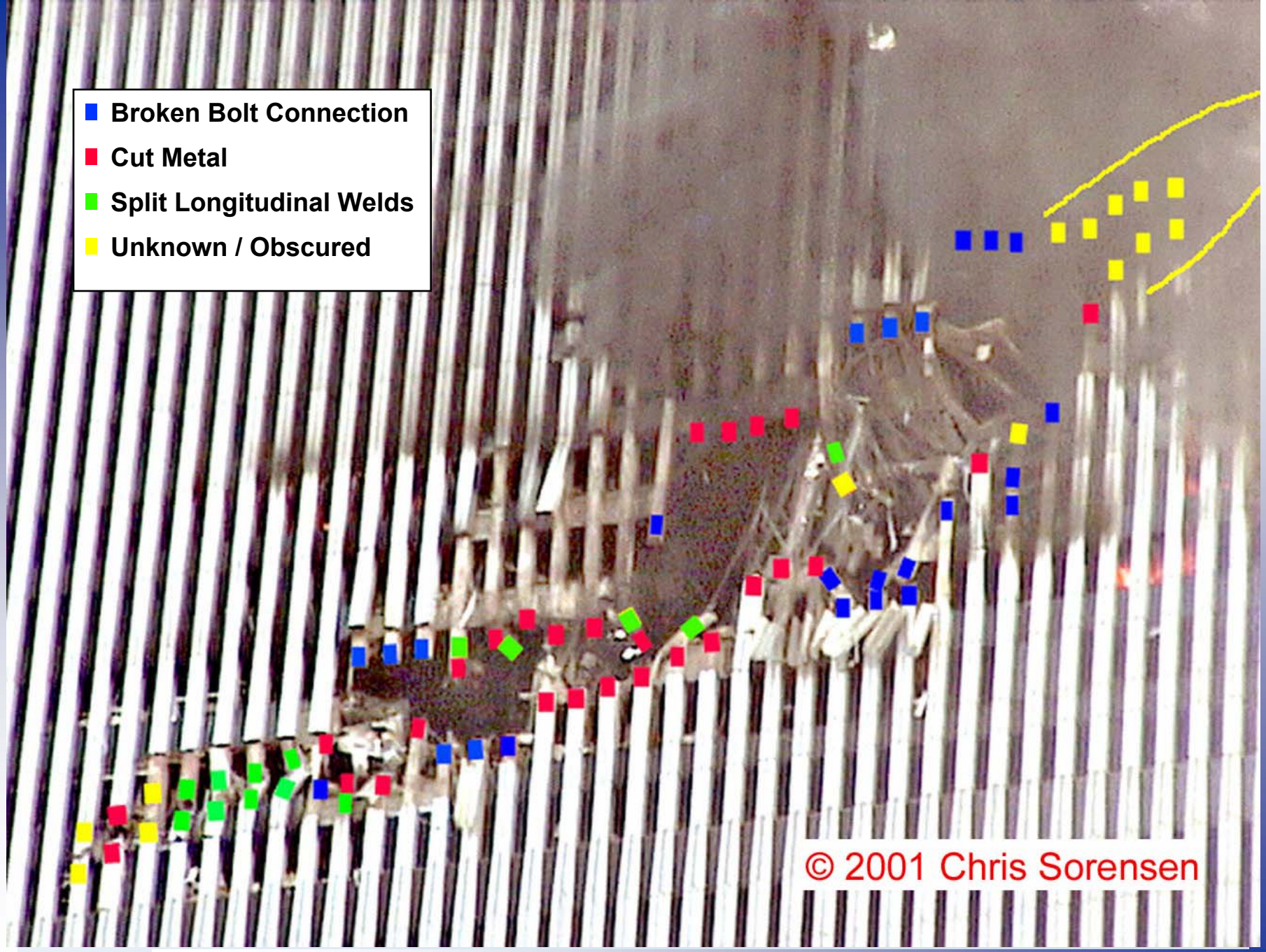
Broken Bolt Connection
Cut Metal
Split Longitudinal Welds
Unknown / Obscured
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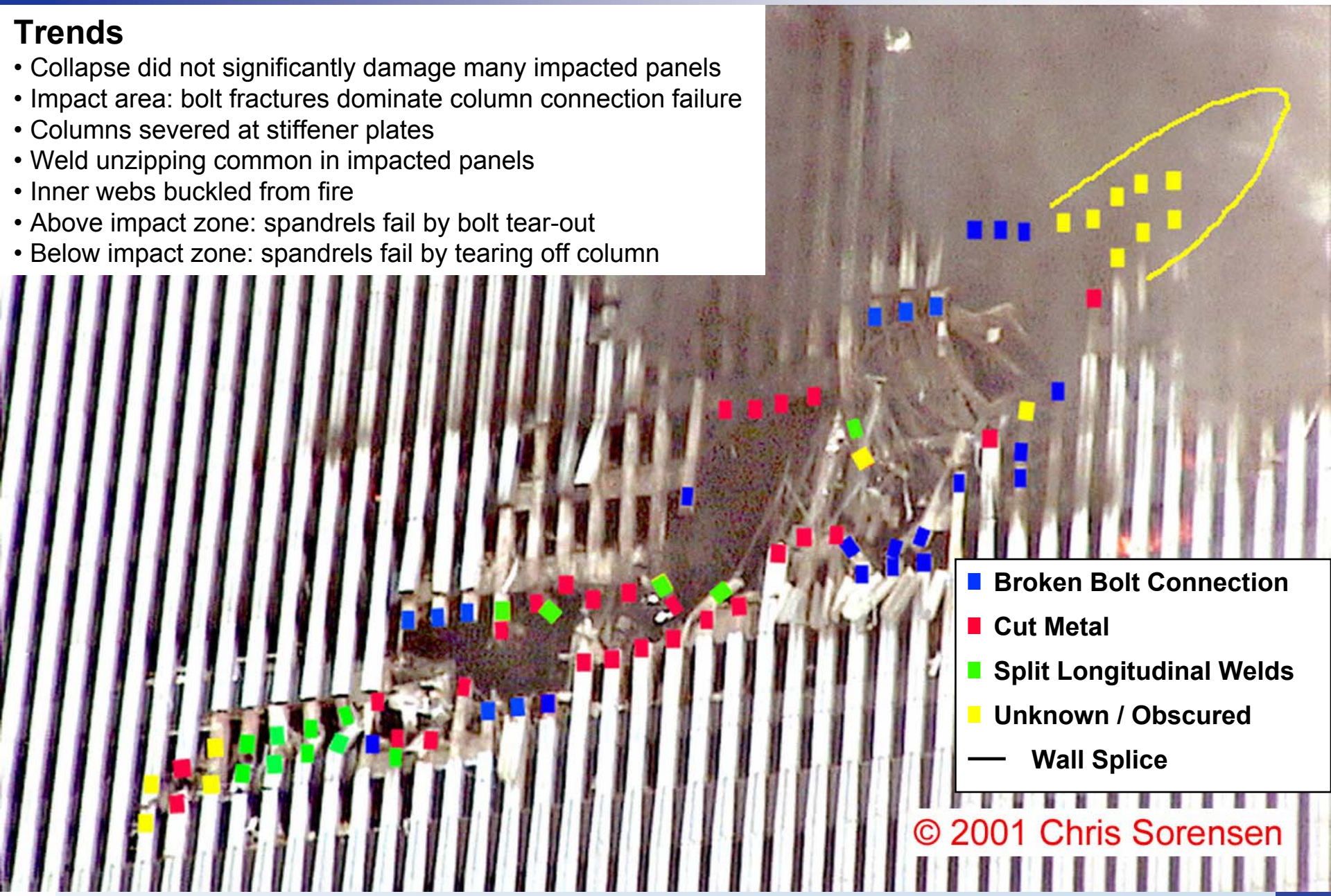
Trends

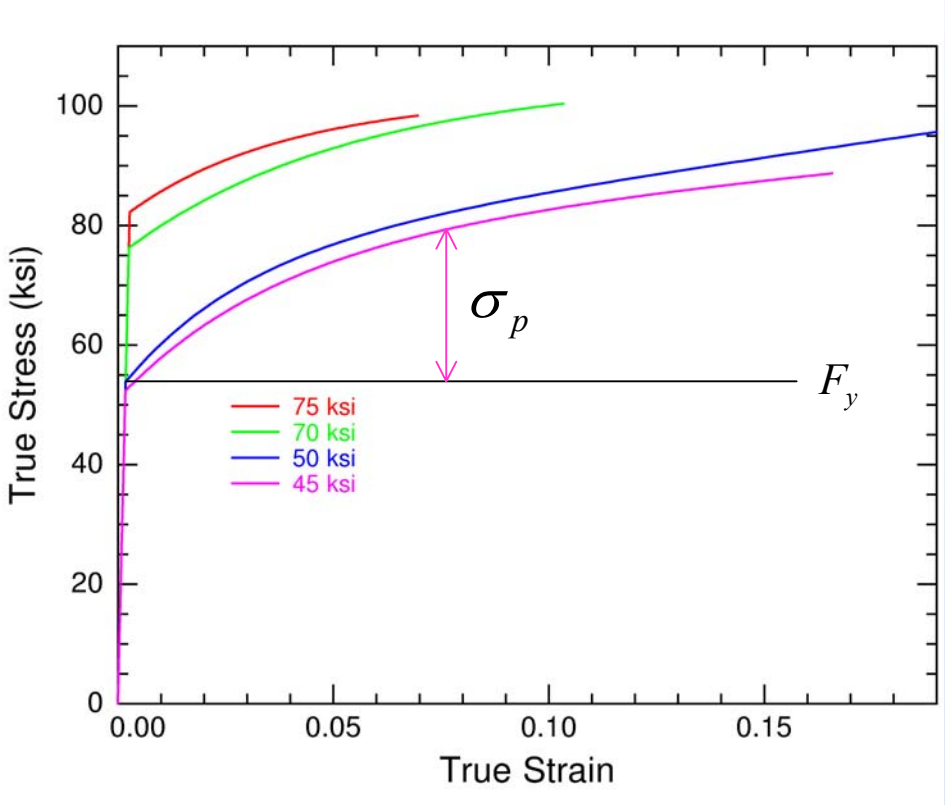
- Collapse did not significantly damage many impacted panels
- Impact area: bolt fractures dominate column connection failure
- Columns severed at stiffener plates
- Weld unzipping common in impacted panels
- Inner webs buckled from fire
- Above impact zone: spandrels fail by bolt tear-out
- Below impact zone: spandrels fail by tearing off column



Task 3 – Determine metallurgical and mechanical properties

- Room temperature tensile properties (229 tests)
  - Perimeter columns and spandrels
  - Core columns
  - Trusses
  - Truss seats (inner and outer)
  - Bolts, welds
- High strain rate properties (117 tensile tests)
  - Perimeter columns
  - Core columns
- High temperature properties (114 tests)
  - Perimeter columns
  - Core columns
  - Trusses
  - Truss seats (inner and outer)
- Physical properties
  - Thermal expansion
  - Thermal conductivity
  - Heat capacity

Model Stress-Strain Curves: Room Temperature



Tensile properties determined for 29 different steels:

- *NIST test values compared with values estimated from literature and mill reports*
- *NIST test values compared with required properties*
- *ideal stress strain curves developed*
- *material parameters supplied for 29 steels*

Curve	Material
1	Core - 36 ksi box column
2	Core - 36 ksi wide flange column
3 - 5	Core - 42 ksi box, 3 plate gauges
6 - 7	Core - 42-50 ksi WF, Groups 1& 2, 3
8 - 9	Core - 42 ksi, 45 ksi WF, Group 4 & 5
10-19	Perimeter – 36-100 ksi, plates 1, 2 & 4
20	Truss – rounds specified as A36
21	Truss – all angles & A242 rounds
22-29	Perimeter – 36-100 ksi, plate 3

Voce nonlinear isotropic hardening:

$$\sigma_p = R_0\varepsilon + R_\infty\left(1-\exp(-b\varepsilon)\right)$$

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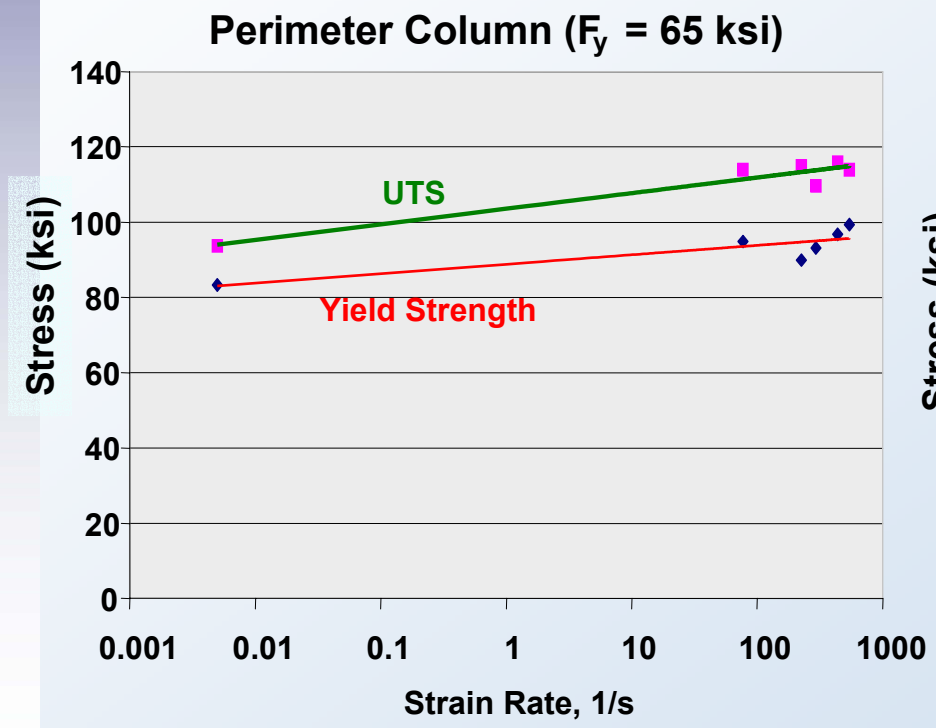
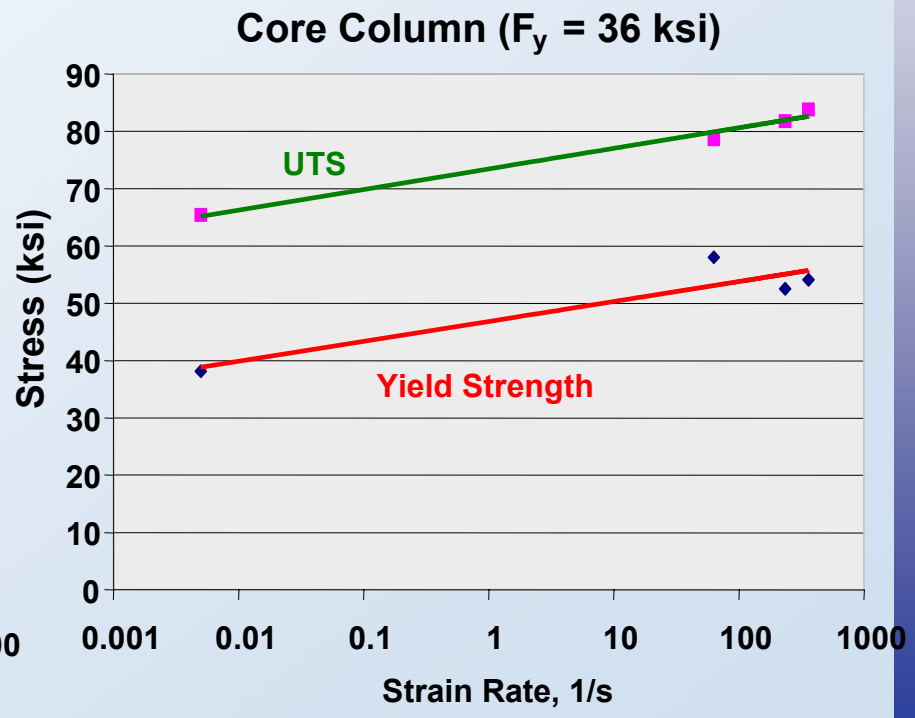
High Strain Rate Behavior: Room Temperature

Yield and Ultimate Strength Increase with Increasing Strain Rates

Higher strength of perimeter columns during impact results in greater reduction of aircraft's momentum. Such data allow more accurate modeling of damage to interior of building.





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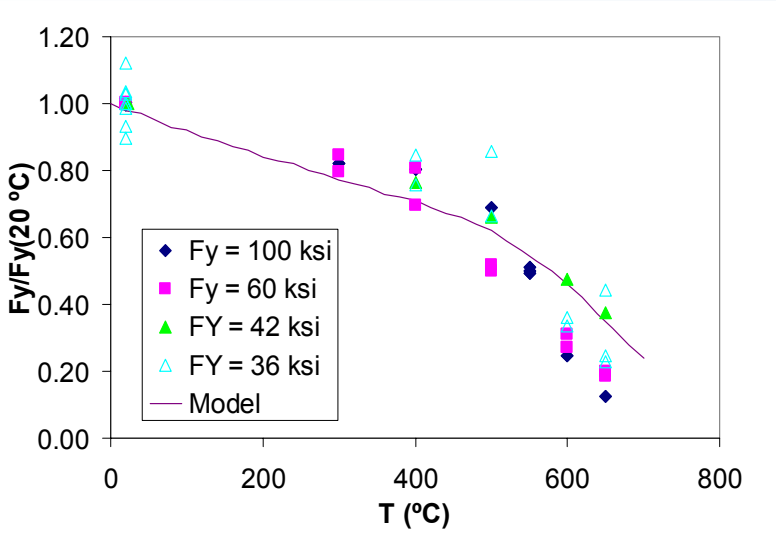
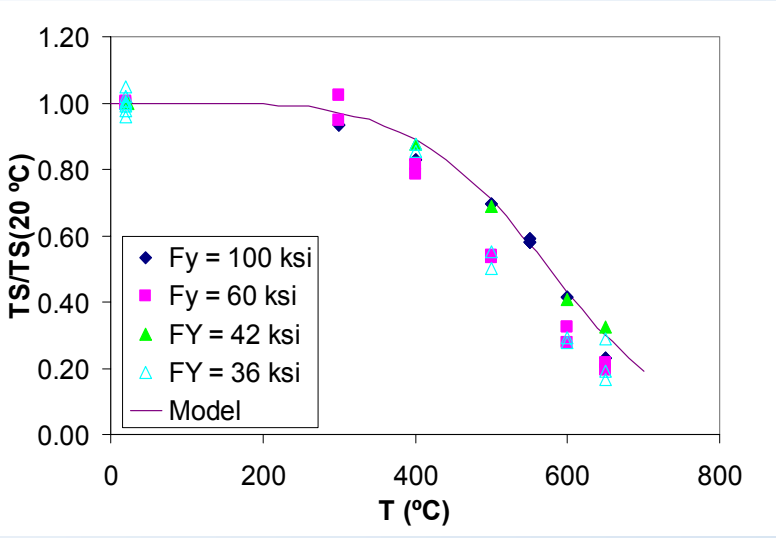
Model Stress-Strain Curves: Elevated Temperature



Yield and Tensile Strength:

- modeled for all steels with universal equation scaled to RT value
- based on literature, corroborated with test data on WTC steel



Creep:

- modeled for all steels with universal equation scaled by TS.
- originally developed for F_y= 36 ksi steel.

Task 3 – Determine metallurgical and mechanical properties - room temperature, high temperature, high strain rate (complete)

- ***Material properties have been determined for:***
  - *all structural steels (29 steels), bolts, and welds*
  - *Strength and modulus as function of temperature*
  - *Strength as function of strain rate for impacted steels*
  - *thermal expansion, heat capacity, and thermal conductivity as function of temperature*

Task 5 - Characterize thermal excursions of steel

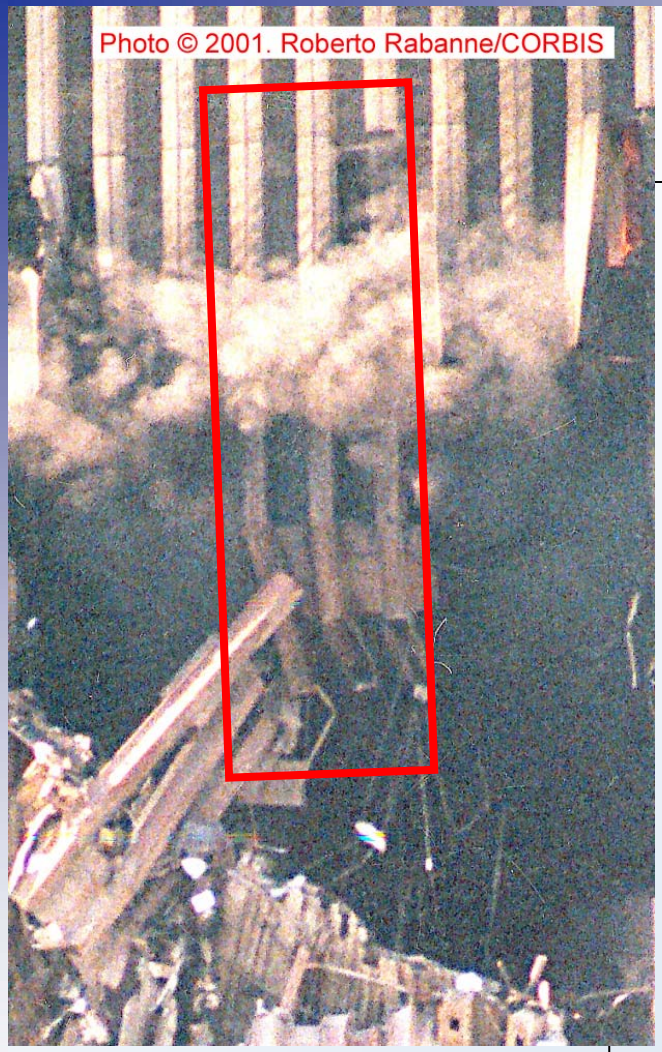
Photographic study

- Recovered panels mapped for pre-collapse exposure to fire

Paint study

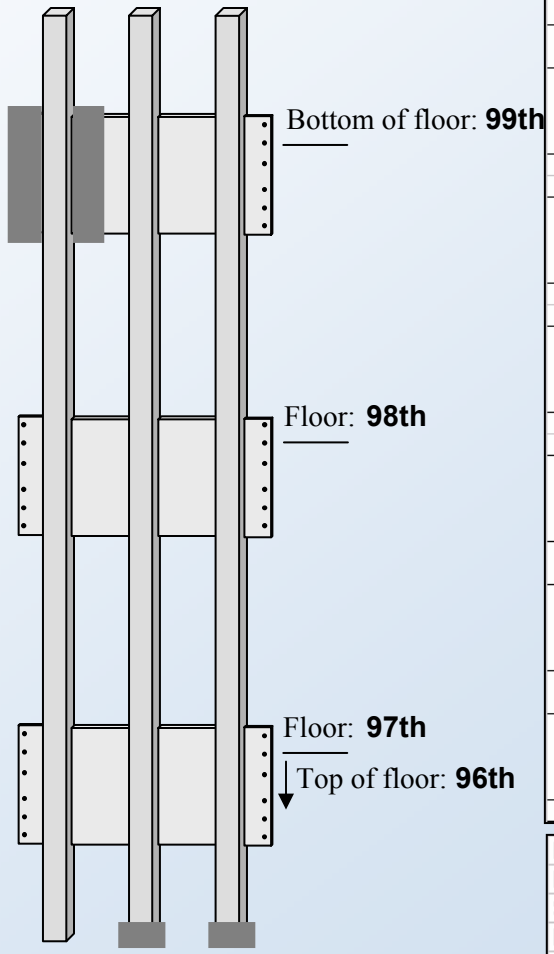
- Paint condition used to map upper limits to temperature exposure
- Few perimeter panels (3 of 160 locations mapped) saw T > 250 °C

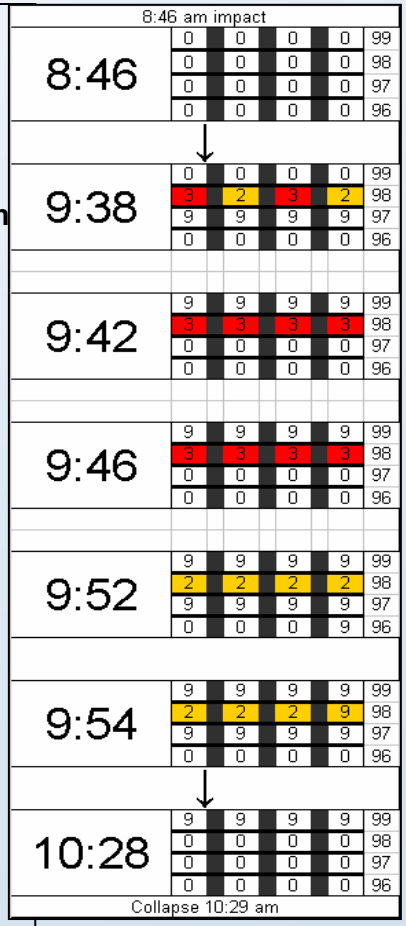
➢ *Analysis complete, report being drafted*



NIST Name:	**M-2**
Panel ID:	**A130: 96-99**
Panel location:	**WTC 1, North face**
Window lines:	**28-31**

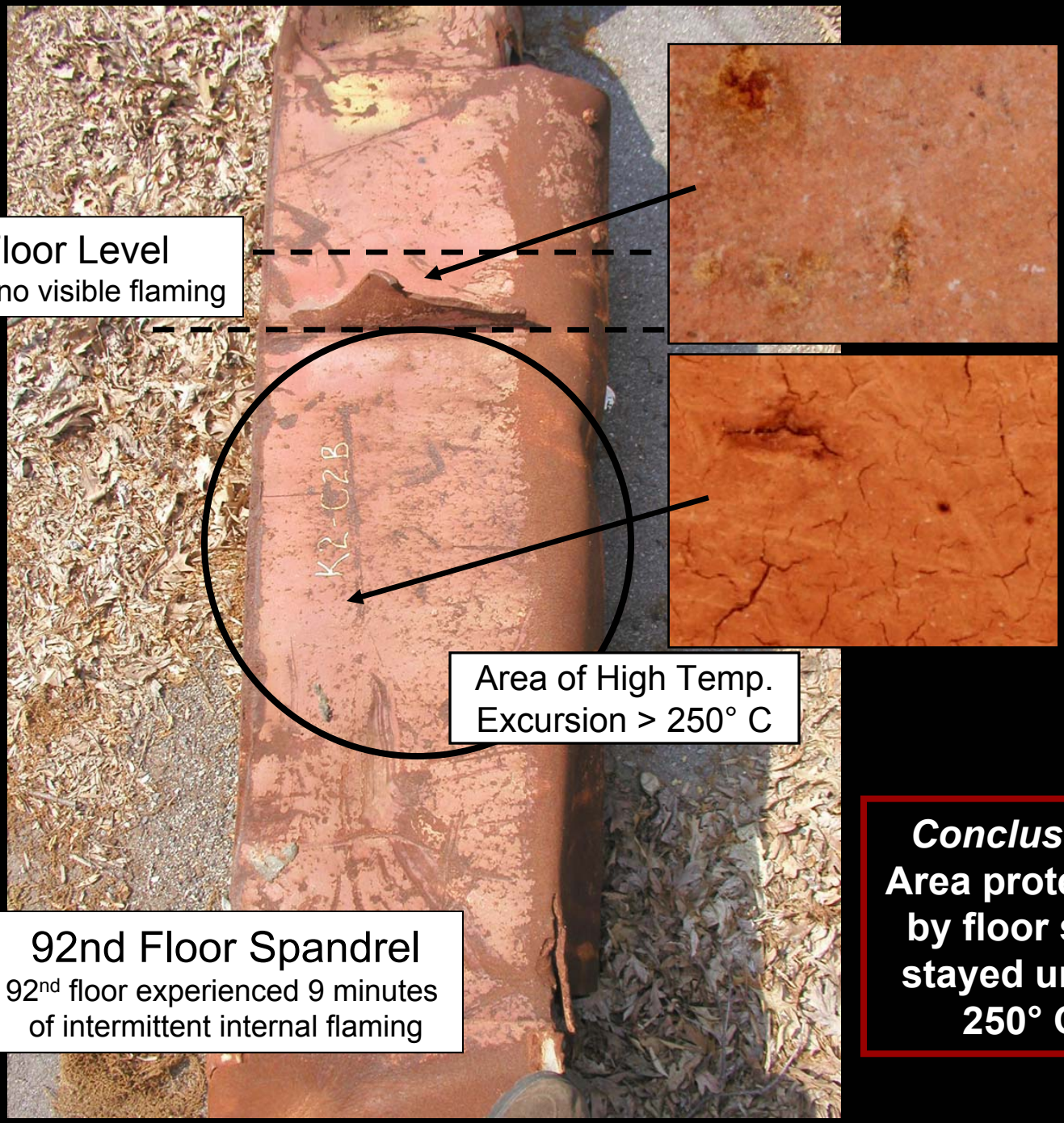
■ **Un-recovered portion of panel**





External flaming	3
Fire inside	2
Spot fire	1
No fire evident	0
No determination	9
Unrecovered portion of panel	#

WTC 1



9:20	9	9	9	9	95
	9	9	9	2	94
	9	0	9	0	93
	0	0	0	0	92
9:26	3	9	9	9	95
	9	9	9	9	94
	9	9	9	9	93
	2	2	2	2	92
9:32	9	9	0	9	95
	9	9	9	9	94
	9	9	9	9	93
	0	0	0	2	92
9:38	0	2	0	0	95
	9	9	9	3	94
	9	9	9	9	93
	2	2	2	2	92
9:42	2	2	0	0	95
	0	0	0	1	94
	0	0	0	0	93
	2	2	2	2	92

Conclusion:
Area protected by floor slab stayed under 250° C

Project 3 Preliminary Findings

- The collection of recovered steel is adequate for the investigation.
  - 236 pieces of steel
  - Regions of impact and fire damage were emphasized in selection
  - 14 specified steel grades for exterior panels
  - 2 specified grades that represent 99 percent of core columns
  - both specified grades for the steel floor trusses
- Analysis of recovered samples of the many grades of steel indicates that, based on stampings on the steel and mechanical tests, the proper steel was supplied to fabricate components as indicated on the engineering drawings.
- Metallography and mechanical property tests indicate that the strength and quality of steel was adequate, typical of the era, and likely met all qualifying test requirements. In many instances, the room-temperature strength exceeded the requirements by 5 to 10 percent.
- Ten different steel companies fabricated structural elements, using steel supplied by at least eight different suppliers; four fabricators supplied the major structural elements from the 9th to the 107th floors.