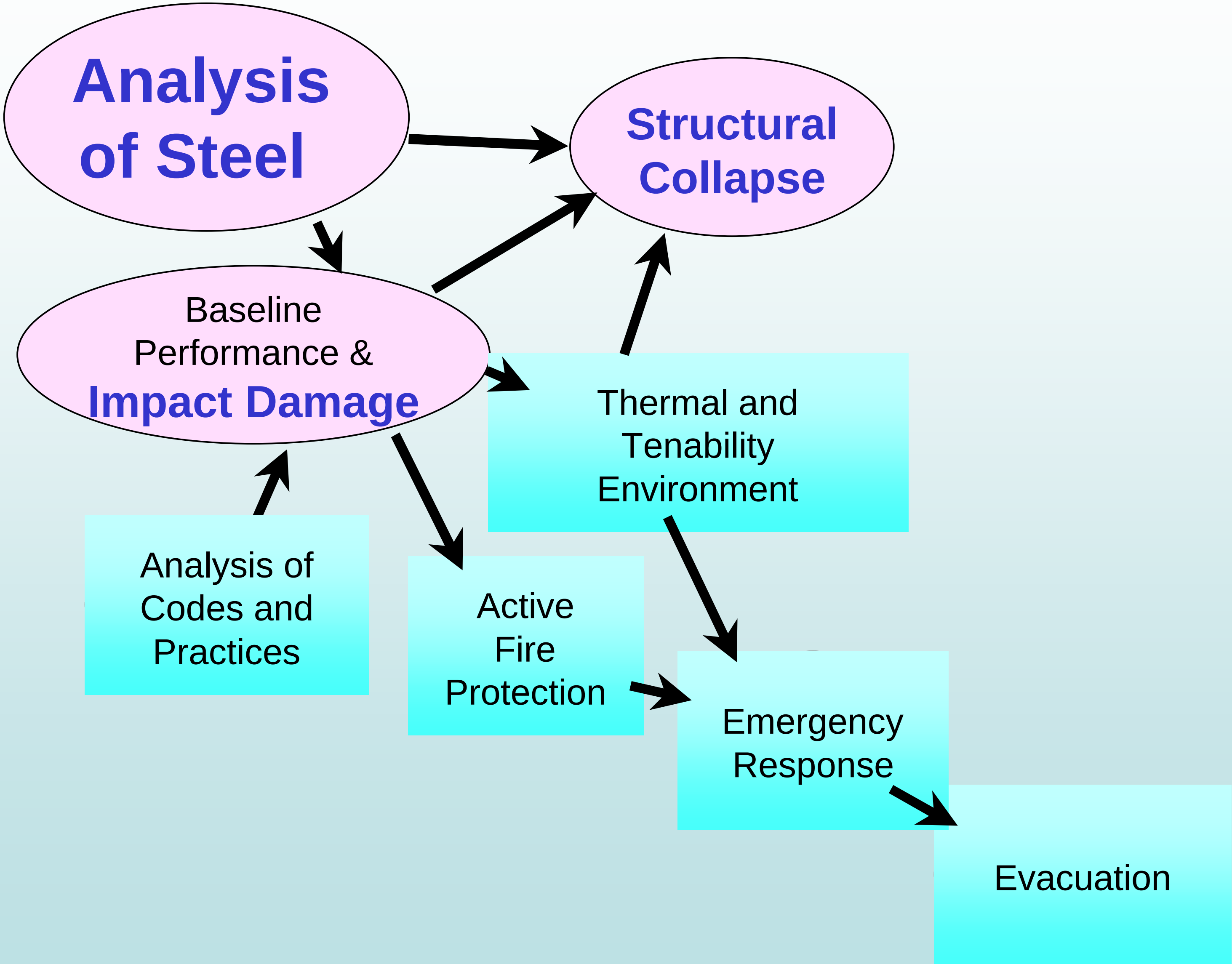
Analysis of Structural Steel *in the* NIST World Trade Center Investigation

Frank W. Gayle
Materials Science and Engineering Laboratory

Richard Fields, Steve Banovic, Tim Foecke, Bill Luecke, Gaithersburg, Md.
Dave McColskey, Tom Siewert, Chris McCowan, Boulder, Co.

National Institute of Standards and Technology

NIST WTC Investigation Projects



Analysis of Steel

Structural Collapse

Baseline Performance & **Impact Damage**

Thermal and Tenability Environment

Analysis of Codes and Practices

Active Fire Protection

Emergency Response

Evacuation

Today’s presentation

I. Structure of Buildings & Steel Inventory

II. Steel Properties and Quality

III. Validated properties to enable modeling

IV. Failure analysis to constrain output of models

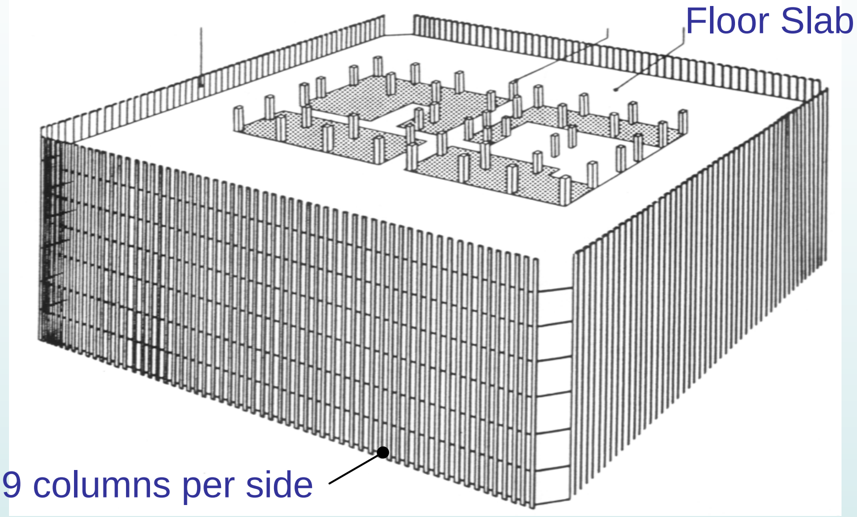
Part I

Structure of Buildings

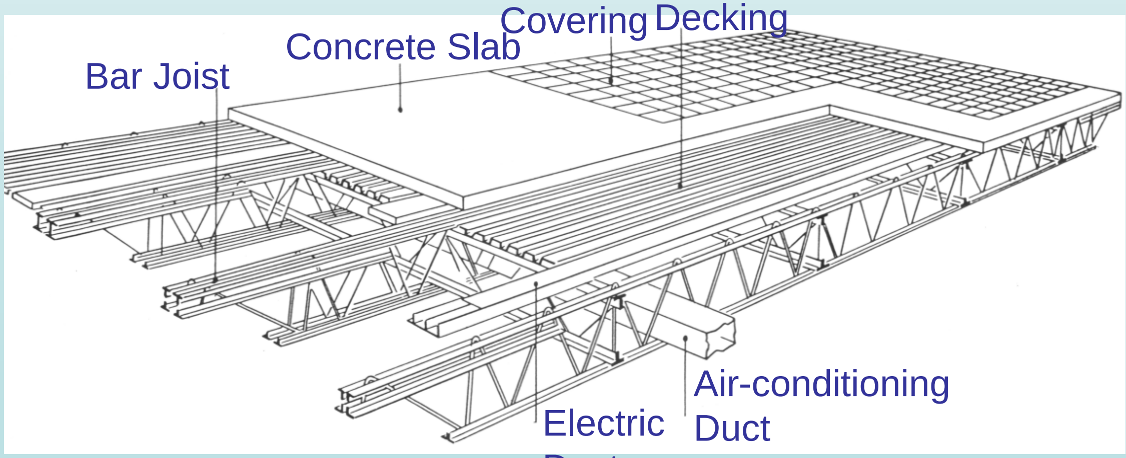
&

Steel Inventory

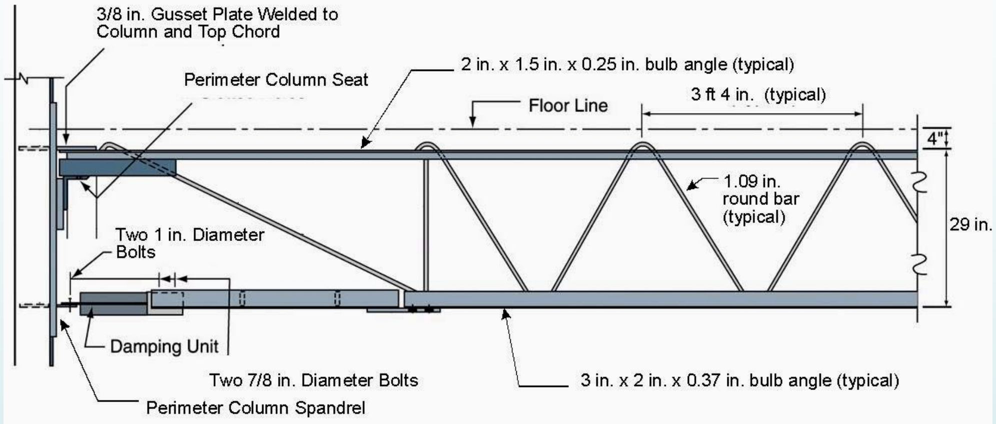
WTC Tower Structural System

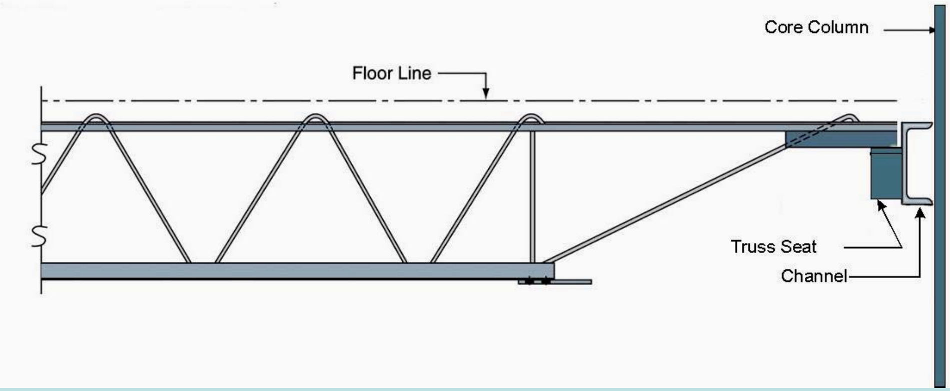


- Innovative structural system when built; incorporated many new and unusual features



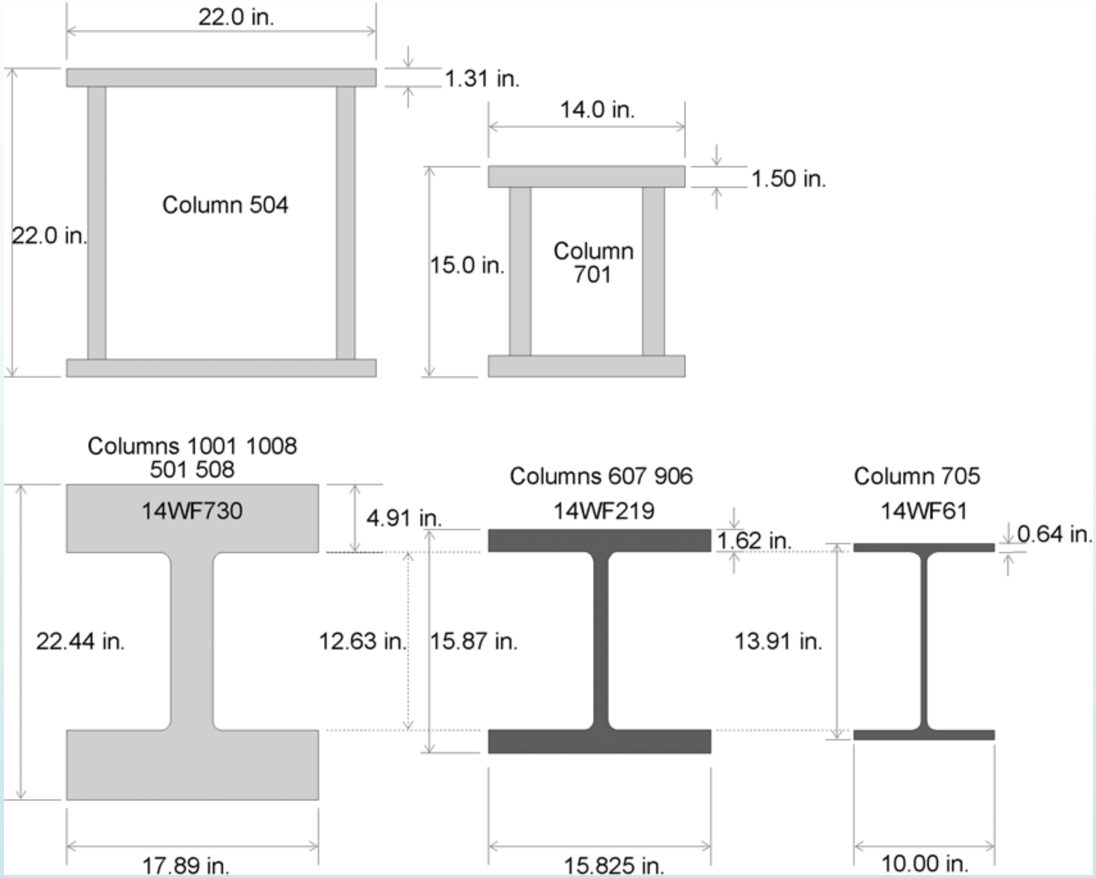
Floor truss assemblies





- Steels: A 36 and A 242
  (36 ksi & 50 ksi)
- Components
  - Angles: 3 sizes, 2 specs
  - Round bars: 5 sizes, 2 specs
- Truss Types
  - 36’ and 60’ lengths plus bridging trusses
  - <u>Dozens of variants</u>
- Fabricated by Laclede Steel
  (fabrication documents found)

Core column assemblies



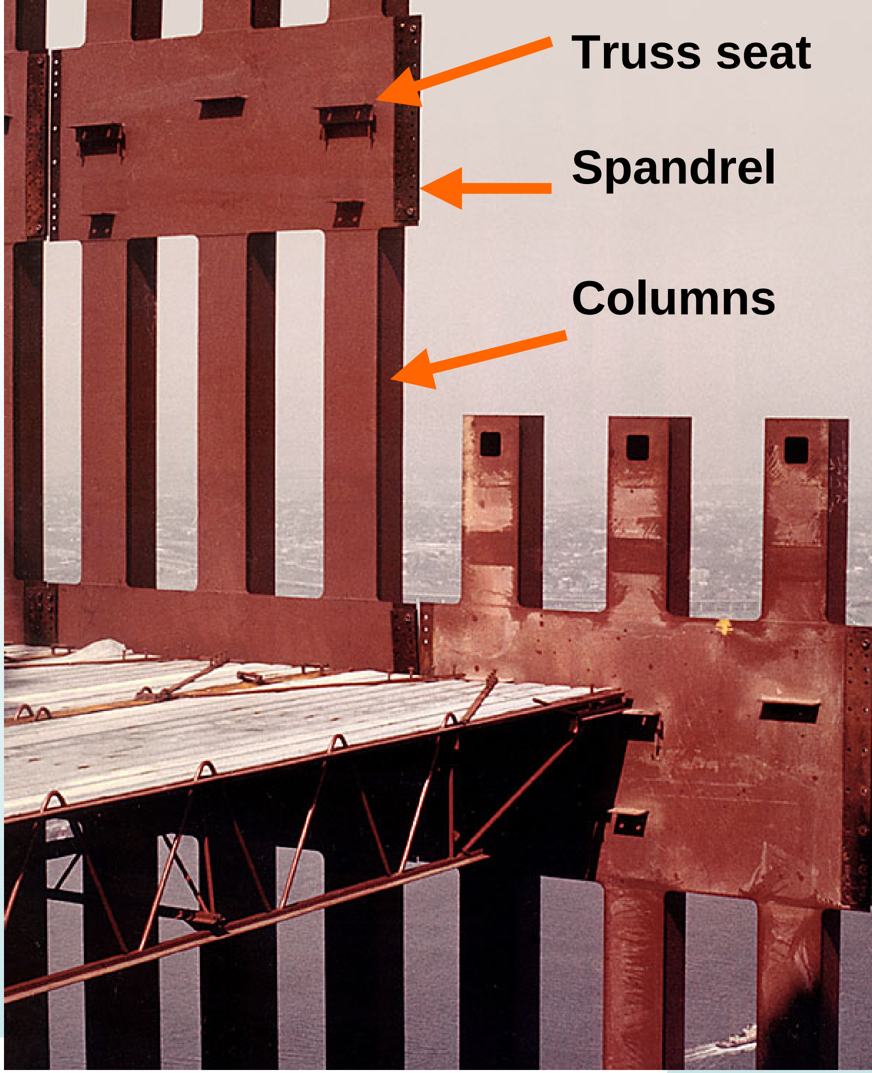
Box columns

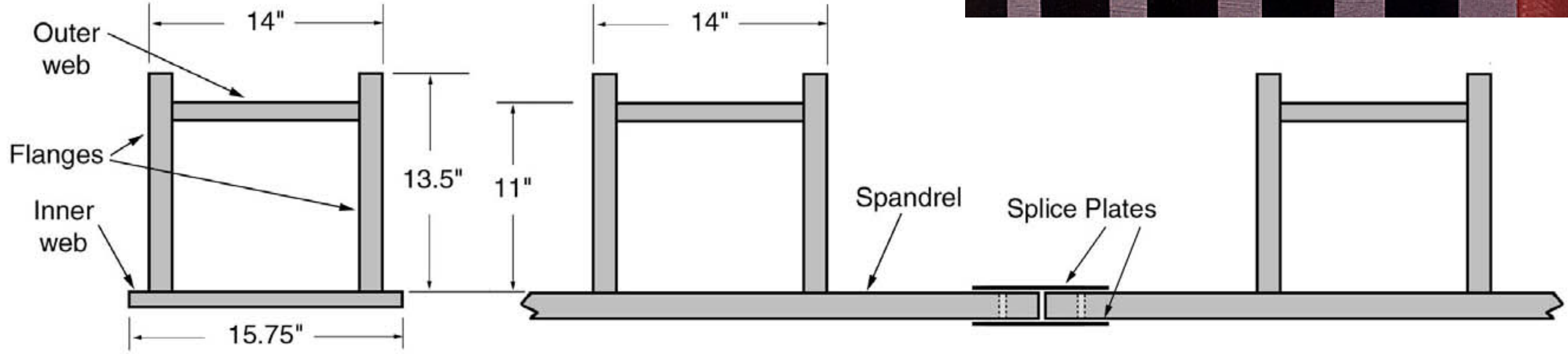
Wide Flange Columns

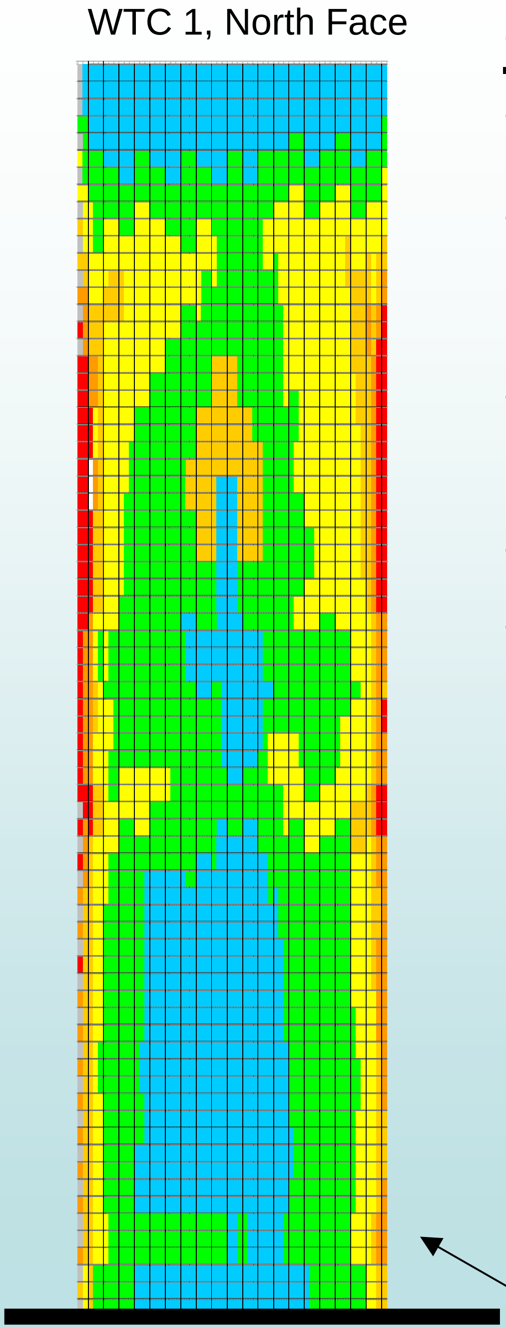
- 4 strength levels: primarily 36 ksi and 42 ksi
- Wide-flange (WF) shapes predominant in fire zone of WTC1
- Mixed shapes in WTC 2 (many box → WF transitions in floor s 80 to 86
- Multiple steel suppliers (!)

Perimeter column assemblies

- Prefab – 3 columns x 3 stories
- 12 strength levels – F_y= 36 ksi to 100 ksi (up to six different strengths in panel)
- Multiple steel suppliers (primarily Yawata)
- Fire and impact zone mostly ¼” plate







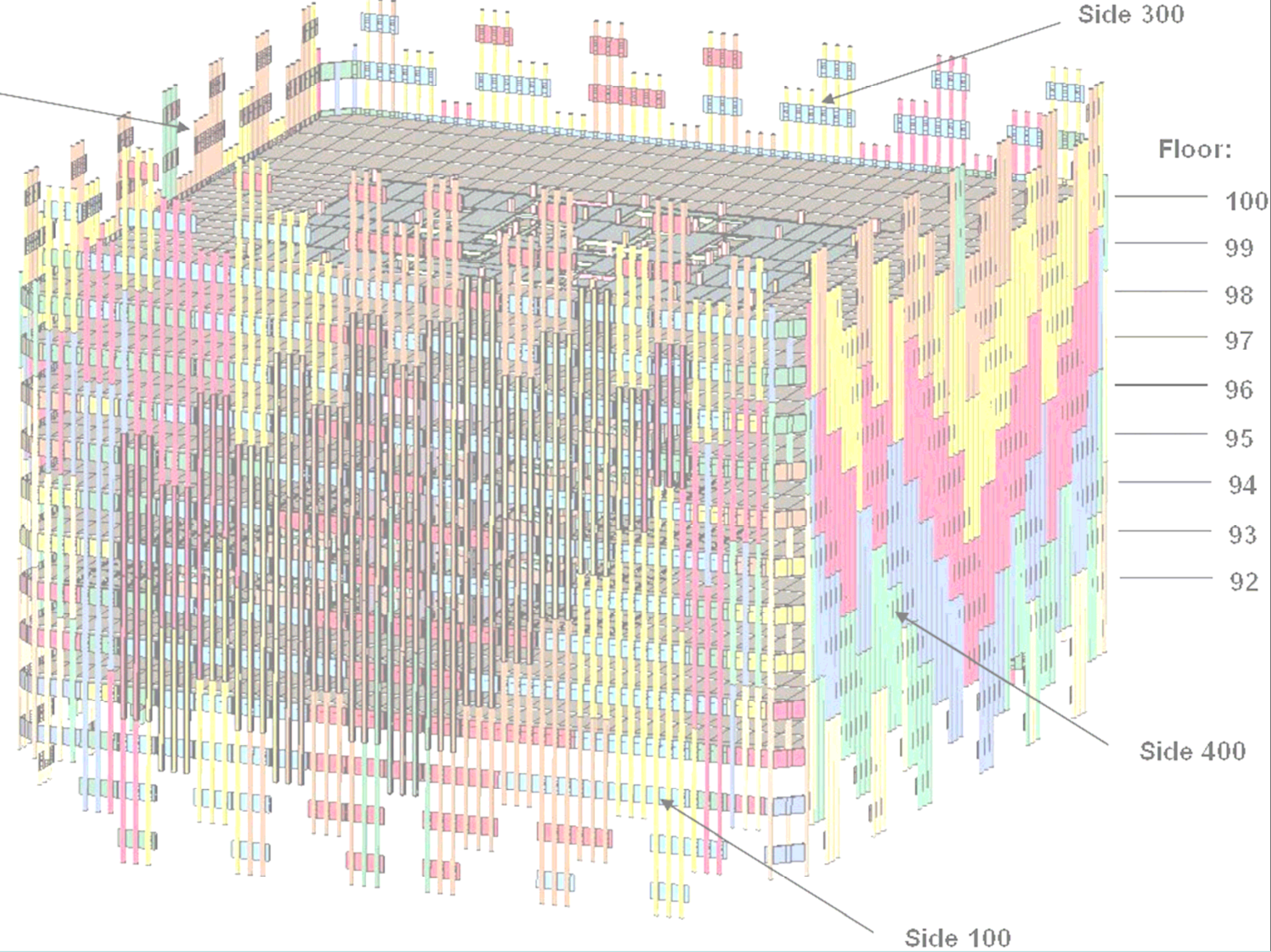
Core columns

- Gravity loads primary factor in design.
- 4 grades of steel
  (99% are 36 and 42 ksi yield strength)
- Conventional (albeit massive!) column & beam construction
- Box columns in lower floors
- Wide flange columns in upper floors

Perimeter columns

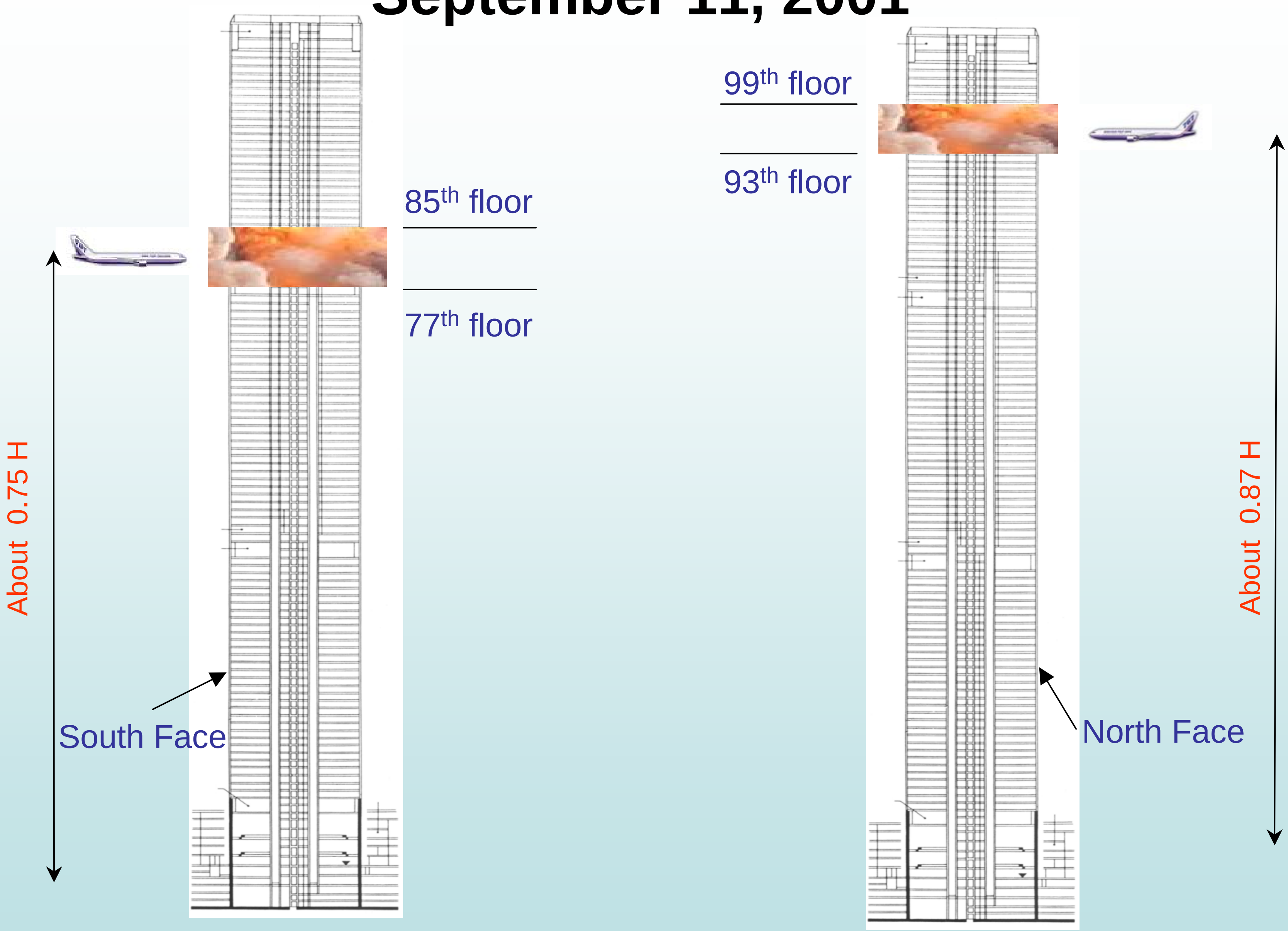
- Wind loads controlled design
- 12 grades of steel used
  (36 to 100 ksi yield strength)
- Arrangement of steel neither symmetric nor the same for the two towers

Simulated distribution of perimeter column yield strengths


Side 300
Floor:
100
99
98
97
96
95
94
93
92
Side 400
Side 100

Sept. 11, 2001

September 11, 2001



85th floor

77th floor

About 0.75 H

South Face

99th floor

93rd floor

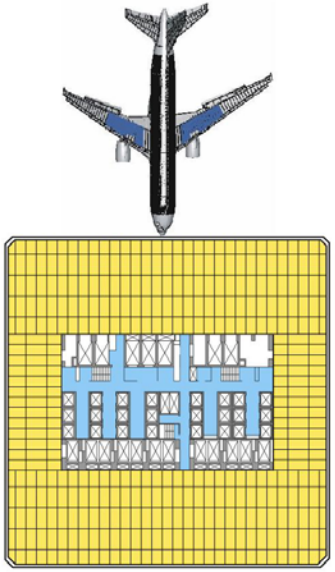
About 0.87 H

North Face

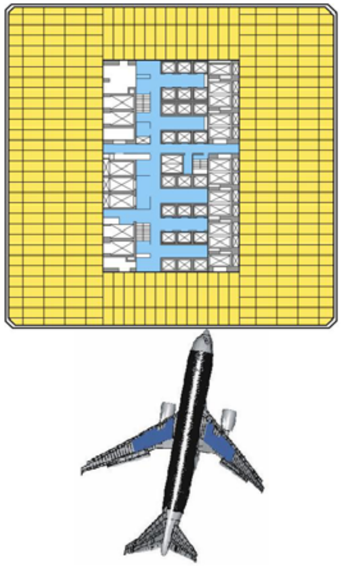
South tower: Hit at 9:03 AM
Collapsed after 56 minutes

North tower: Hit at 8:45 AM
Collapsed after 1 hour, 43 minutes

Point of impact:
Close to the center
and nearly normal
to the building



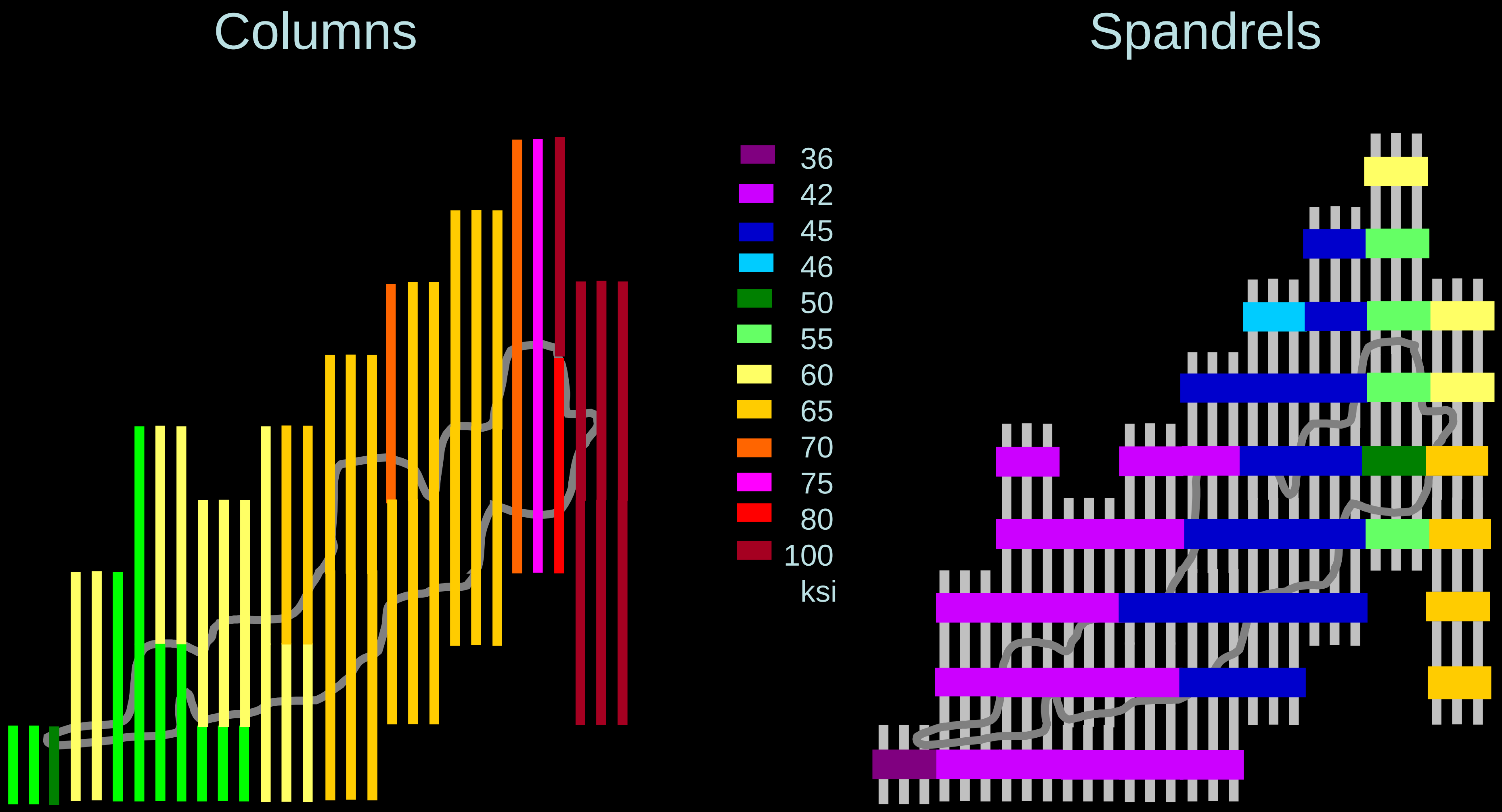
WTC 1



WTC 2

Point of impact:
Close to the corner
and with an angle

All 12 grades of steel involved in impact



Steel strength in panels damaged by aircraft impact into WTC2

Characterization of the Steel

Initial Task - Collect and catalog physical evidence

- **<u>Inventory of Structural steel</u>**
- Design specifications
  (sections & F_y; derived from 10,000 pages design docs)
- Material specifications (ASTM, etc)
- Supplier production information
    - Yawata Steel (now Nippon Steel)
    - Laclede Steel
    - …

1.5 million tons of debris shipped to NJ salvage yards

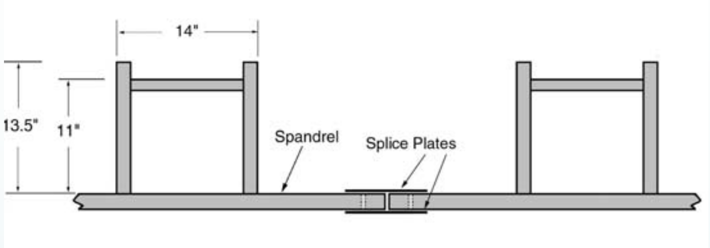
Steel Search, Collection, Logging and Shipping to NIST

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

~ 1.5 million tons of debris
1/4-1/3 steel
Much recycled immediately (overseas)

Salvaged Steel at NIST

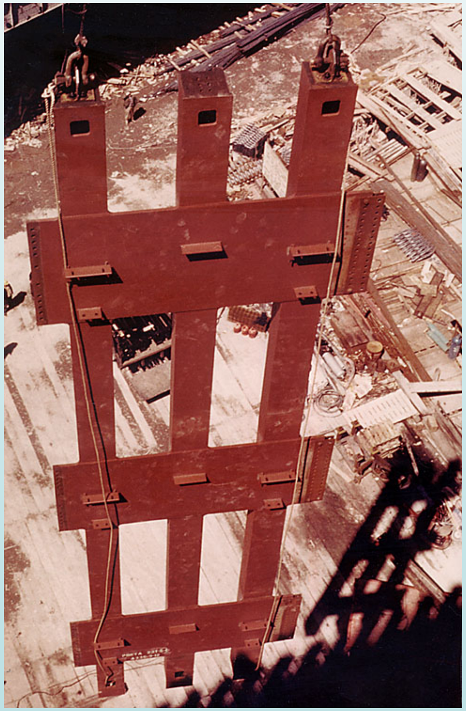
Catalog of Steel – *identified perimeter panels*



42 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 12 grades available for test***



WTC 1

- 26 panels
- 22 near impact floors
  - 4 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

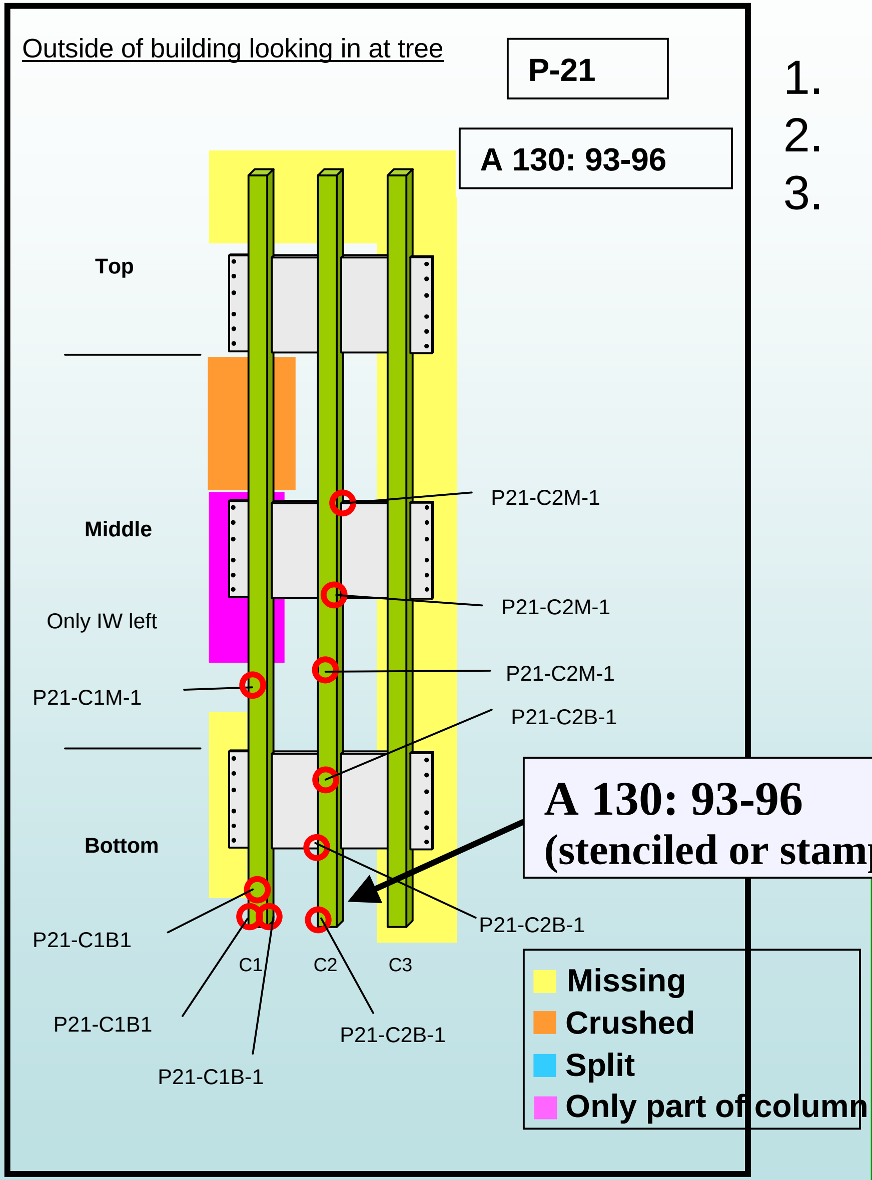
➢ *samples of 2 grades (36 and 42 ksi) of both box and wide flange columns, configurations which represent 99% of core columns in the towers.*

Core box column

Core wide flange (WF) column

DOCUMENTATION OF SAMPLE REMOVAL

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

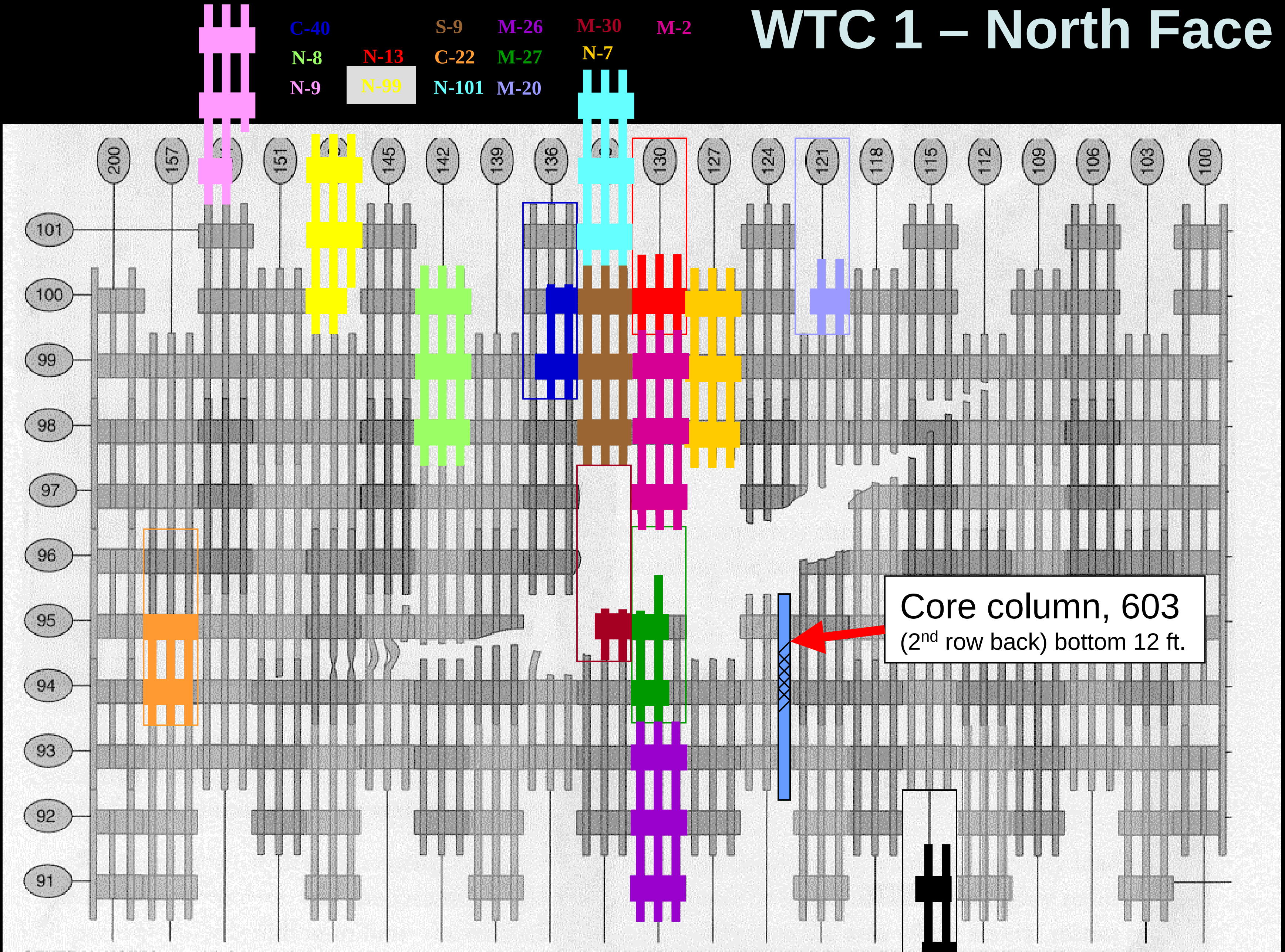


🟨 Missing
🟧 Crushed
🟦 Split
🟪 Only part of column

A 130: 93-96
(stenciled or stamped)

Documentation extremely important!

WTC 1 – North Face

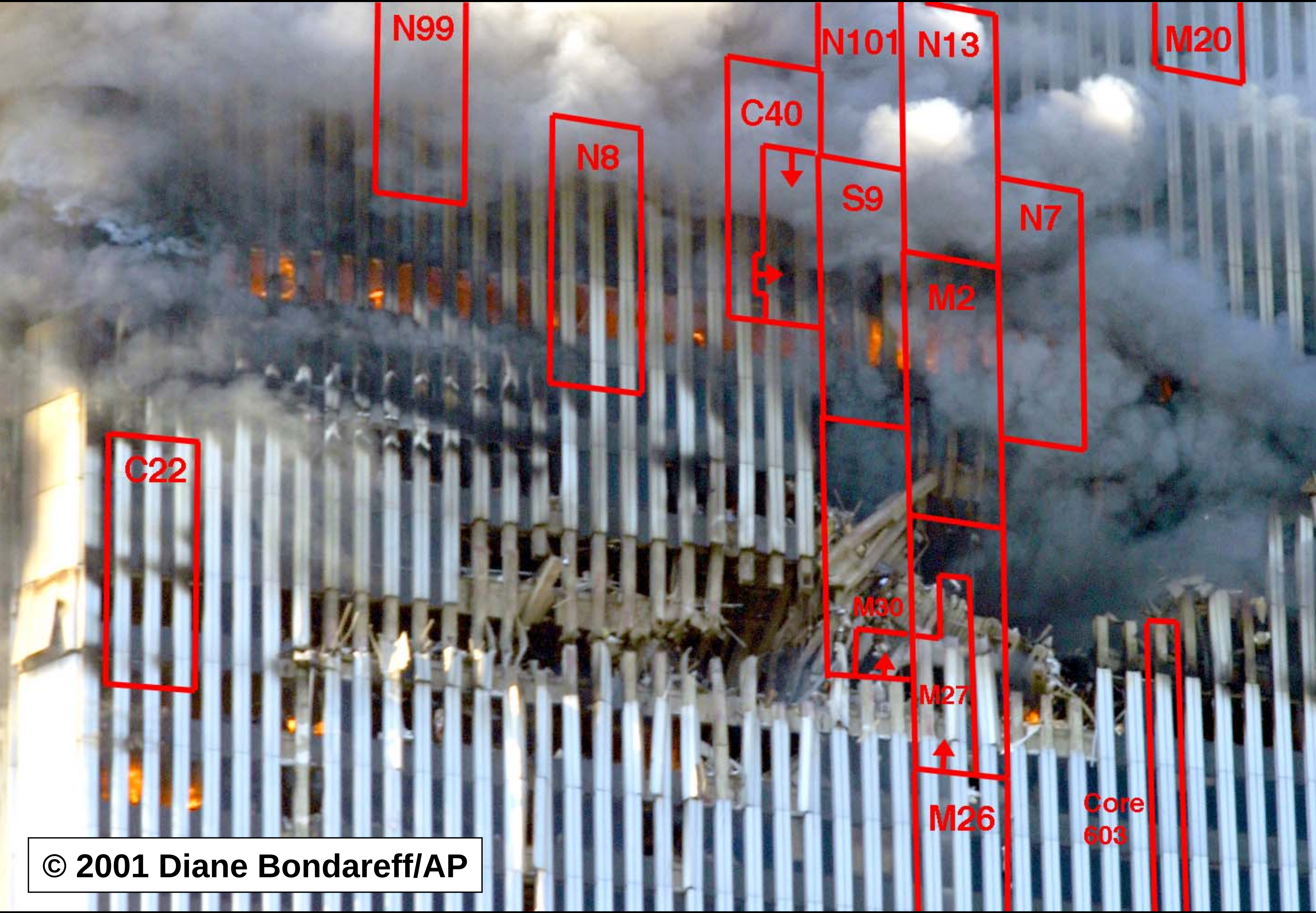


Core column, 603
(2nd row back) bottom 12 ft.

GENERAL NOTES: (1) Column damage captured from photographs and enhanced videos. (2) Damage to column line [illegible]1-115 at level 98 is estimated.

Figure 2-16 Impact damage to exterior columns on the north face of WTC 1.

WTC 1 – North Face



© 2001 Diane Bondareff/AP

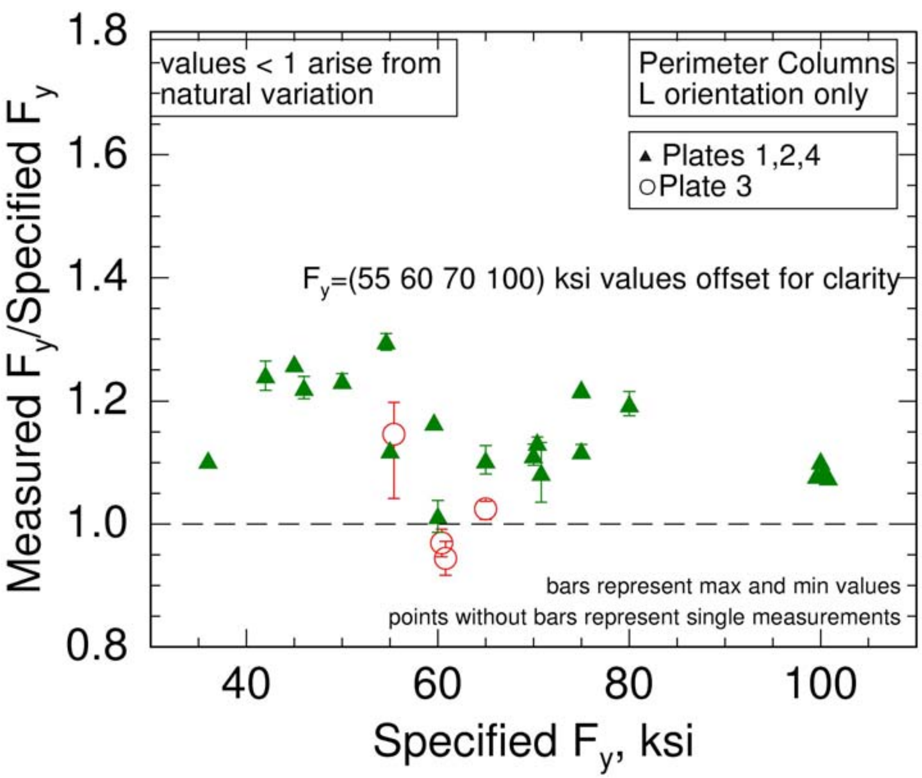
Part II

Steel Properties and Quality

Analyze steel properties and quality

- **Goals**
  - (1) assess the quality of steel with respect to design strength levels
  - (2) assess the quality of steel with respect to 1960’s era steel practice
- **Protocols**
  - Tensile tests (ASTM E-8) on all relevant strength levels
  - Additional tensile tests on steels from fire and impact zones
- **Limitations**
  - Not possible to identically recreate original mill test conditions
  - Recovered steel often damaged in collapse and recovery efforts
  - Natural variability of steel properties (mill test vs product test)
- **Materials tested**
  - Perimeter columns: examples of all strength levels and identified mills
  - Core columns both common strengths, both shapes (WF and box)
  - Trusses and seats: both strength levels, both shapes, multiple examples of truss seats.

Perimeter column properties



- Examples of all strength levels
- Excess strength is consistent with 1960's era plate practice
- Appearance of some NIST tests with measured/specified < 1 is consistent with natural plate variability
- Differences in test technique also contribute (NIST rate vs. mill test rate
- ASTM A 6: "…testing procedures are not intended to define the upper or lower limits of tensile properties at all possible test locations within a heat

Chemistry

All plates consistent with Yawata or (presumed) Bethlehem V-series specification

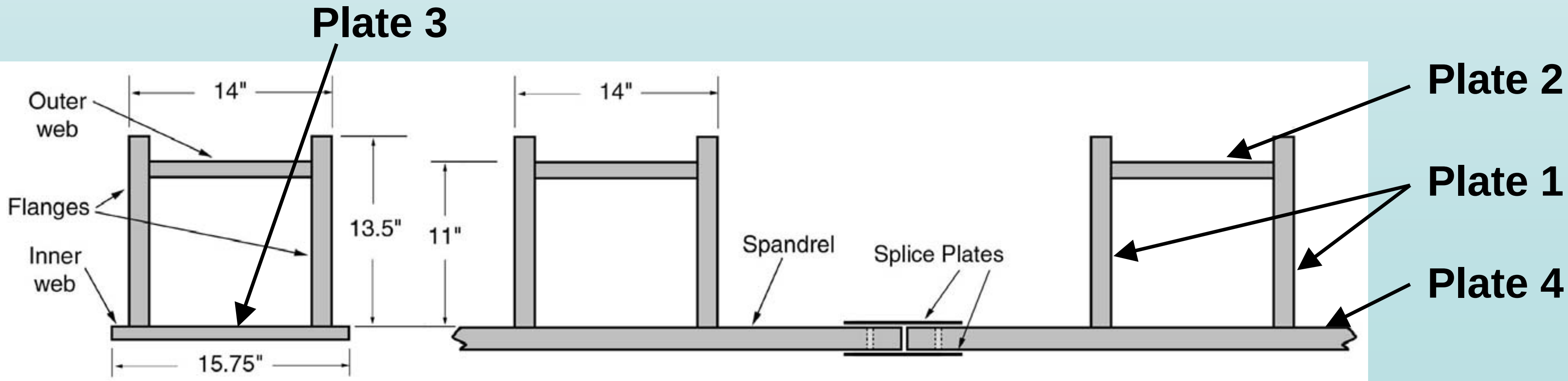


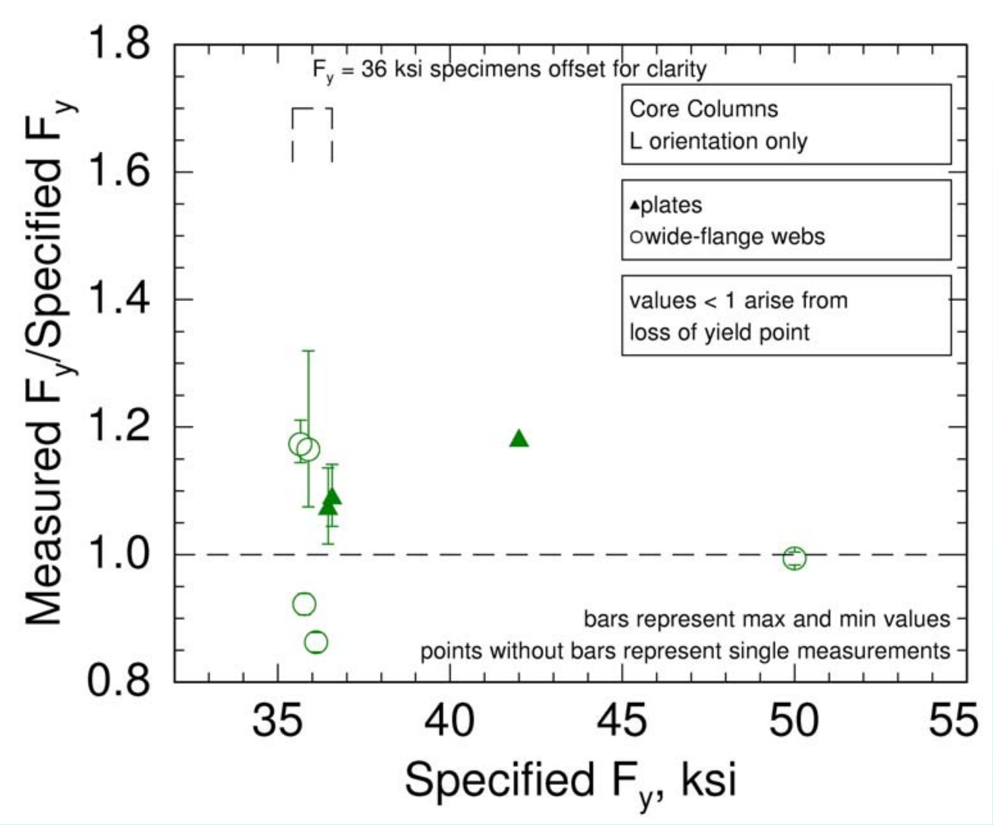
Plate 3

Plate 2

Plate 1

Plate 4

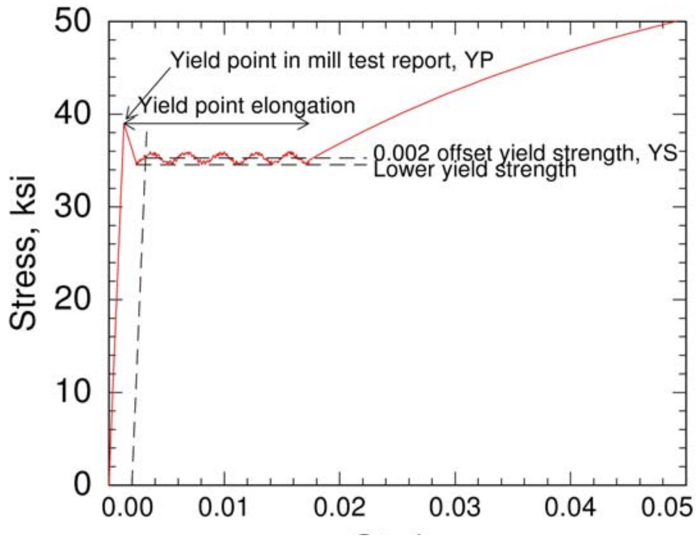
Core column properties

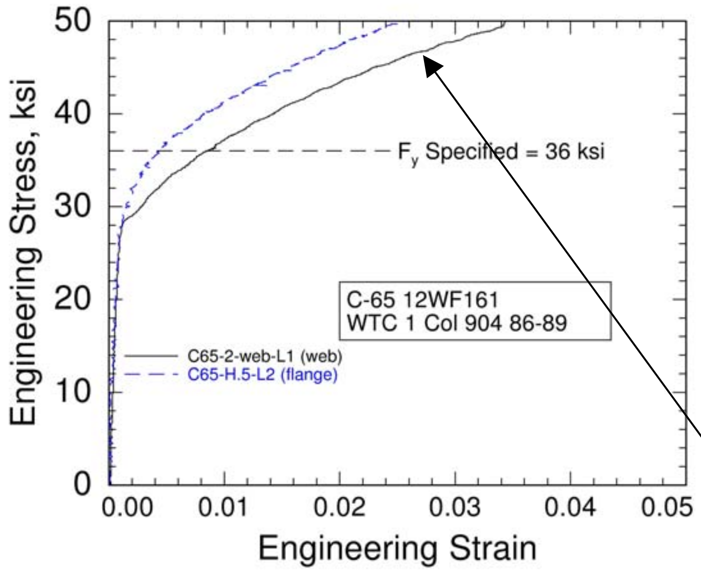


- 4 wide-flange (WF) columns (36 ksi, 42 ksi)
- 3 box columns (36 ksi, 42 ksi)
- 1 beam (50 ksi)
- Specimens with measured/specified <1 exhibit evidence of prior deformation
- Chemistry: 36 ksi plates and shapes are consistent with the requirements of A 36

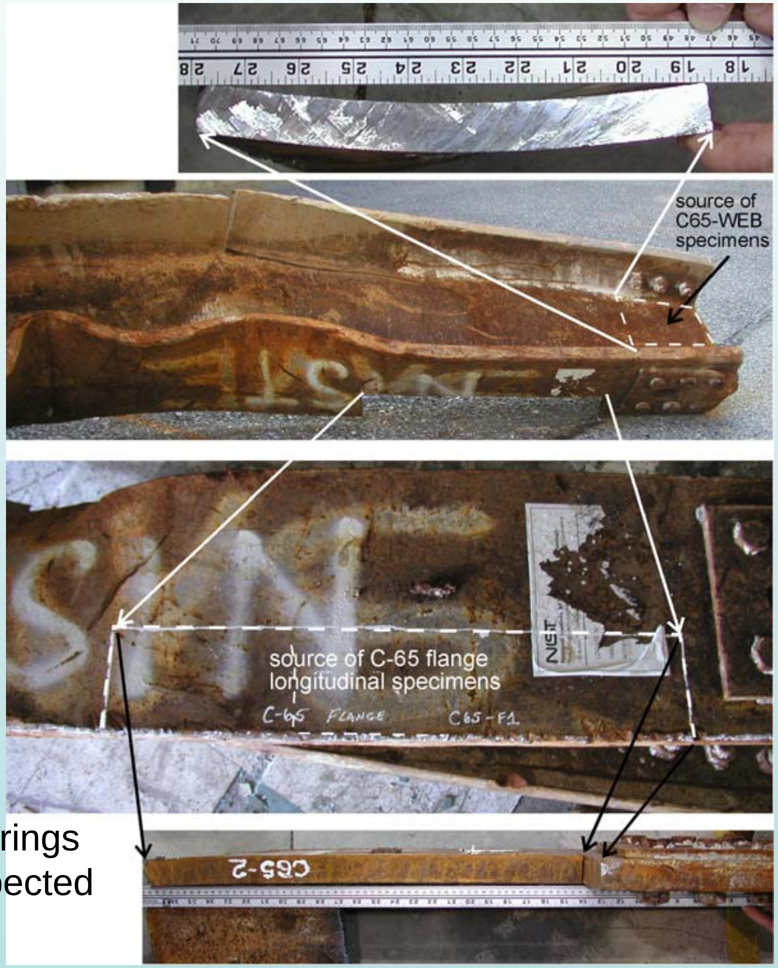
Core columns: damaged specimens

- Low-strength steels are qualified on yield point
- *YP/YS* can be > 1.1
- Mechanical damage can remove *YP*
- Most recovered core columns are heavily deformed

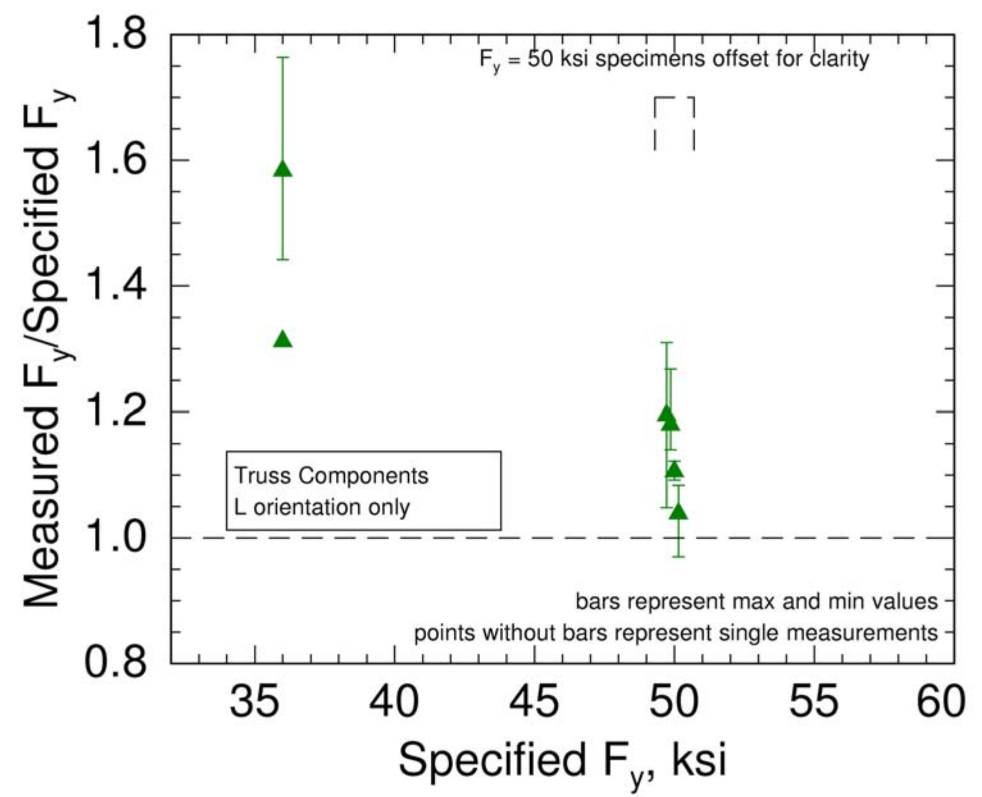




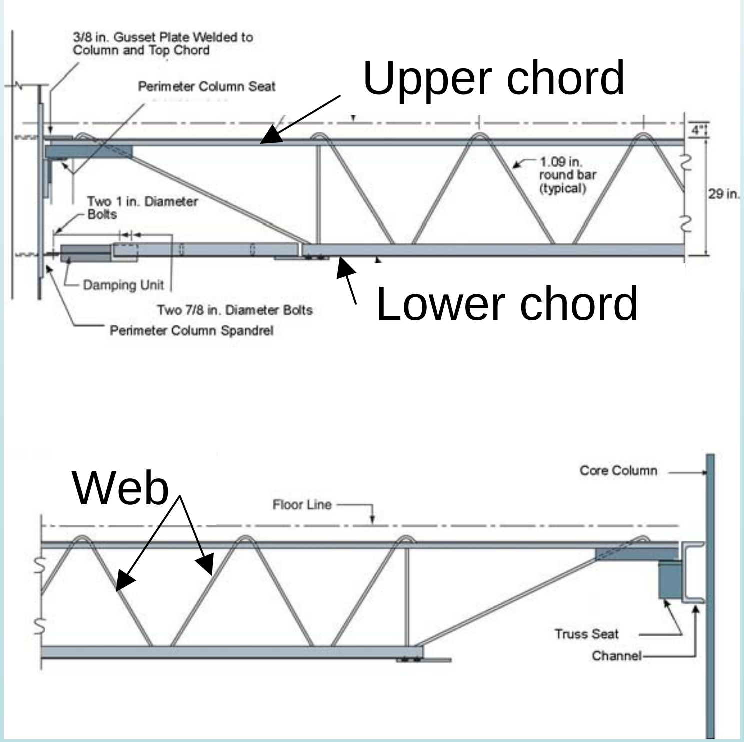
Work hardening brings strength up to expected value by e=0.03



Truss component properties

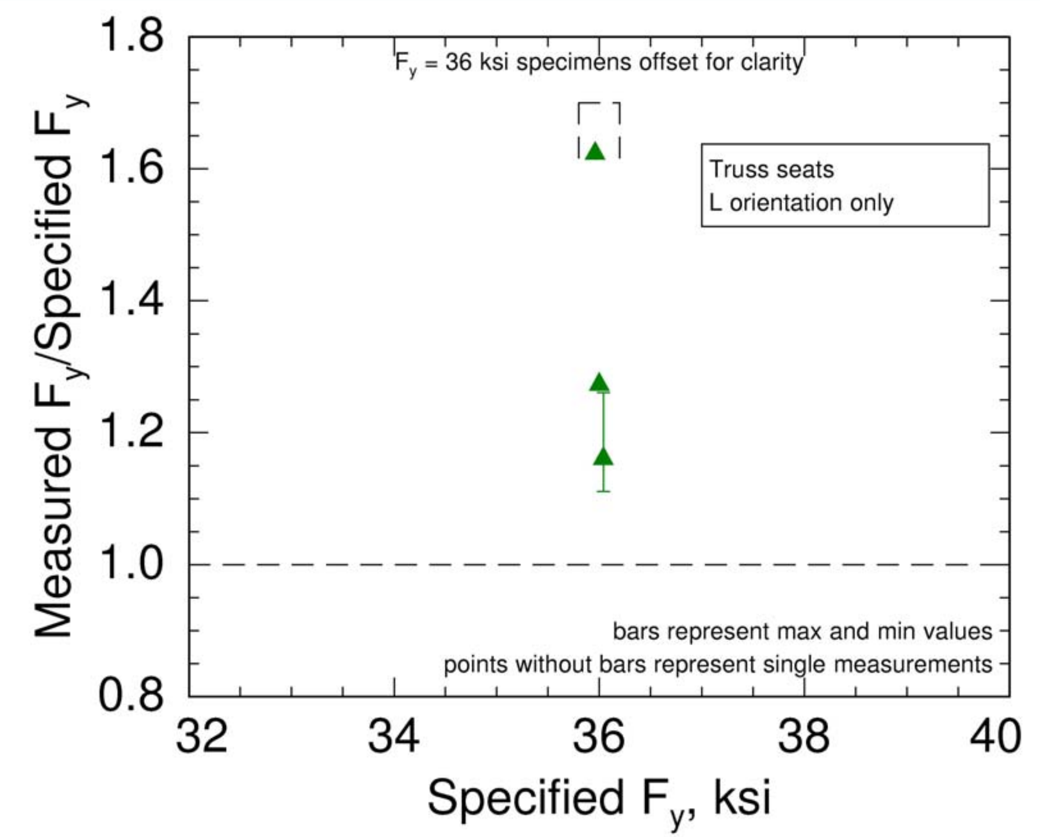


- A 36 F_y=36 ksi
  - –Lower chord and web of 60’ trusses
- A 242 F_y = 50 ksi
  - –Both chords and web of 36’ trusses
  - –Both chords of bridging trusses
  - –Upper chord of 60’ trusses
- Chemistry requirements of A 36-66 and A242-66 are similar



- **Chemistry**
- F_y = 50 ksi and F_y = 36 ksi steels are often similar (microalloyed with V)
- F_y = 50 ksi steels are consistent with requirements of A 242-66, but are similar to modern A 572

Truss seat properties



- All truss seats specified with F_y=36 ksi
- Chemistry of all seats consistent with A36

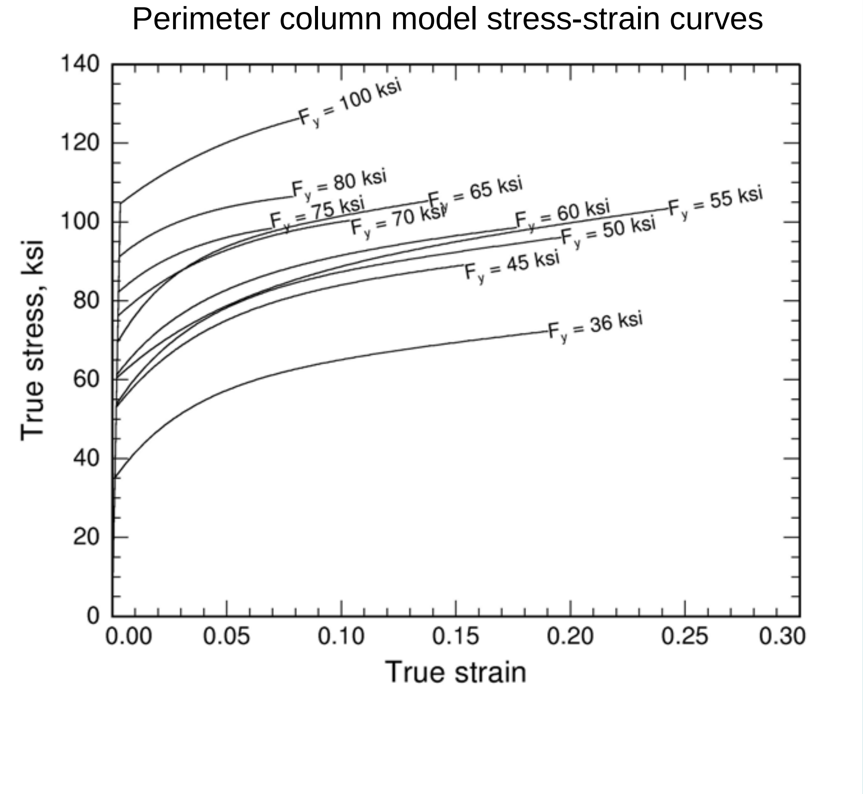
Part III

Validated properties to enable modeling

Properties modeled

- Room-temperature stress-strain behavior
  - Based on tests to assess steel quality
  - Form baseline for high-rate and elevated-temperature behavior
- Room-temperature strain rate sensitivity of strength and ductility
  - for airplane impact studies
- Elevated temperature elastic modulus
  - for fire studies
- Elevated-temperature stress-strain behavior
  - for fire studies
- Elevated-temperature creep behavior
  - for fire studies
- Impact properties
  - Using Charpy tests to screen for brittle behavior at high rates
  - Not covered here

Model properties: stress-strain curves



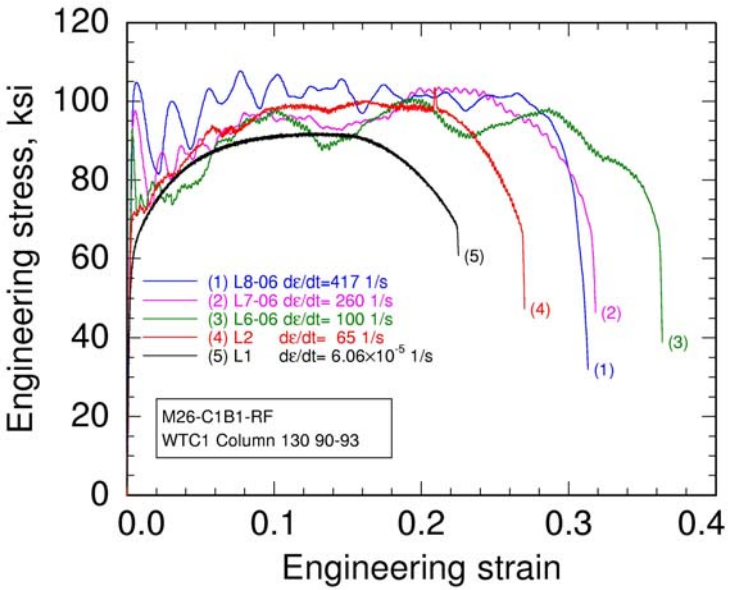
Perimeter column model stress-strain curves

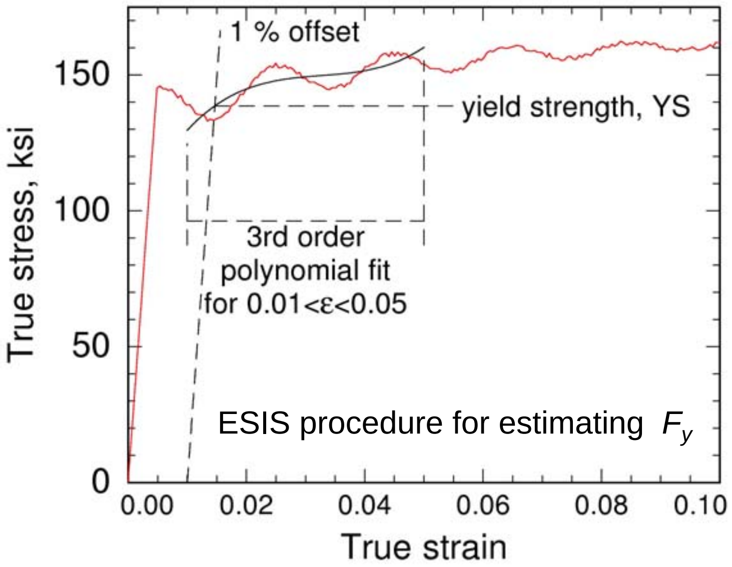
Plasticity modeled using Voce equation

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

- **Goal:** provide model stress-strain curves for each relevant steel
- **Methodology**
  - 1. Elastic portion has RT value = 29.7 Msi
  - 2. Plastic portion modeled from NIST data
  - 3a Perimeter column F_y evaluated from NIST data and surviving mill test reports
  - 3b Core column F_y evaluated from historical averages
  - 4 Yield strength corrected to zero strain rate using historical strain rate sensitivities
  - 5 maximum strain = strain at TS
  - 6 high-rate curves based on these data

Properties: strain rate sensitivity





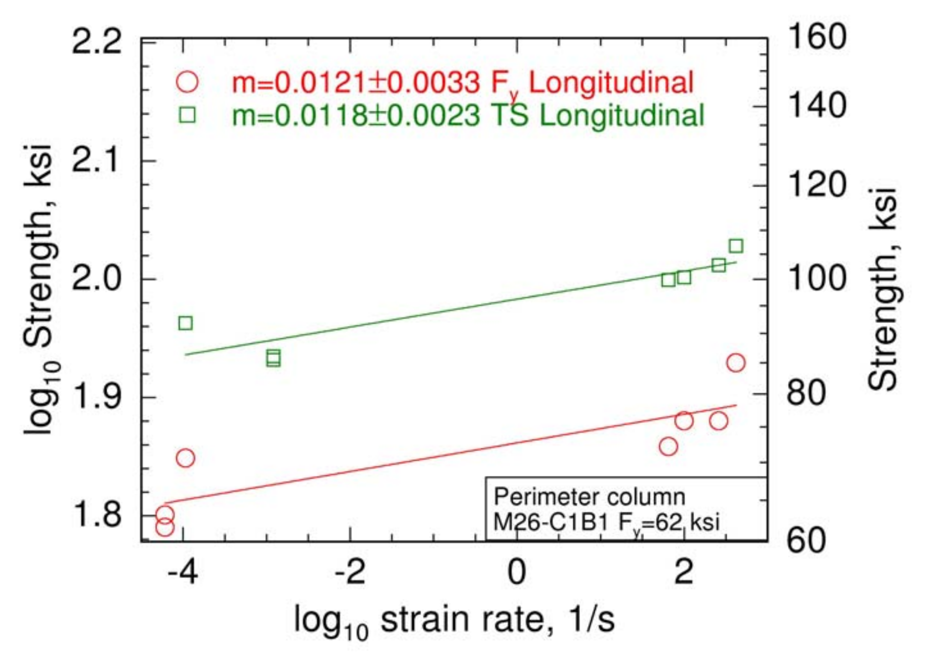
ESIS procedure for estimating F_y

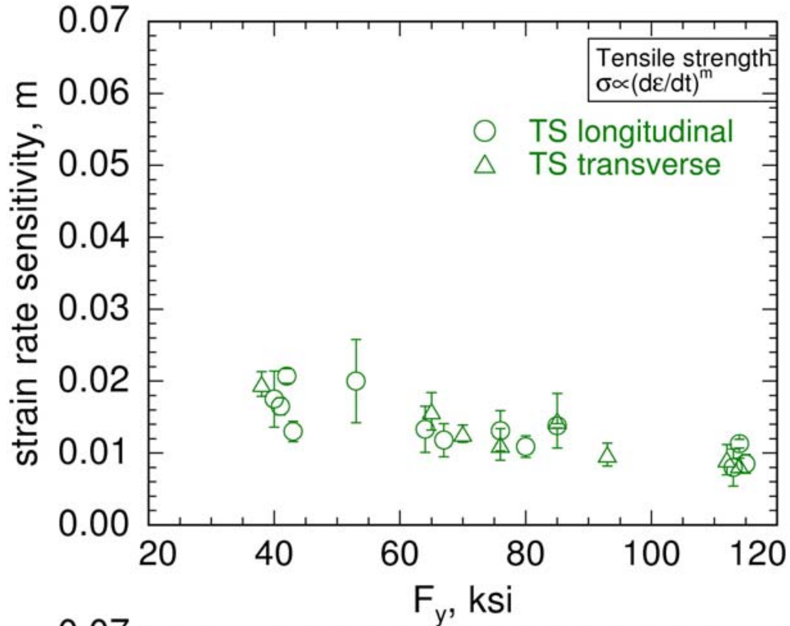
- **Methodology**
  - High-rate tensile tests
  - 8 perimeter columns
    50 ksi < F_y <100 ksi
  - 5 core columns
  - 50 s-1 < de/dt < 500 s-1
    (appropriate for impact rates)
  - No curve smoothing
  - Evaluate F_y using ESIS procedure
- **Results:**
  - No catastrophic ductility loss

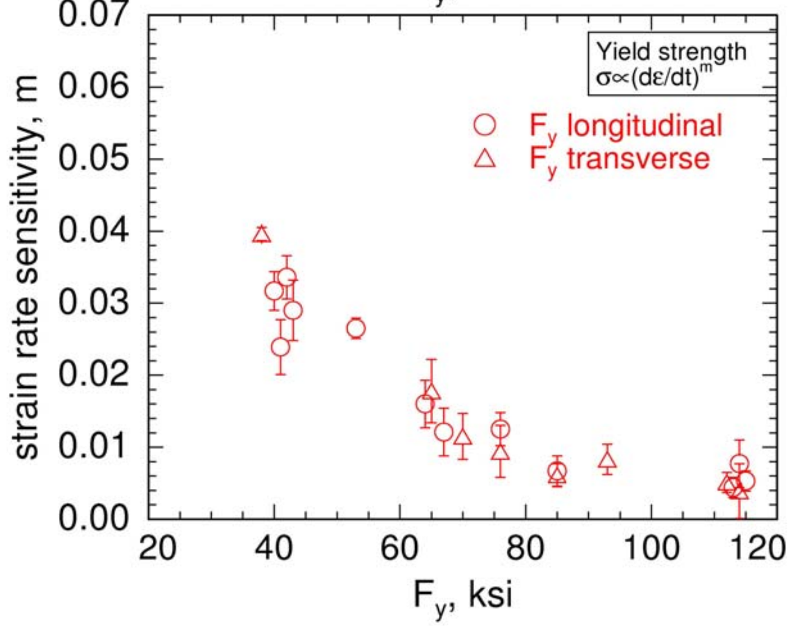
Properties: strain rate sensitivity

$$\sigma_1 = \sigma_0 \dot{\varepsilon}_1^m$$

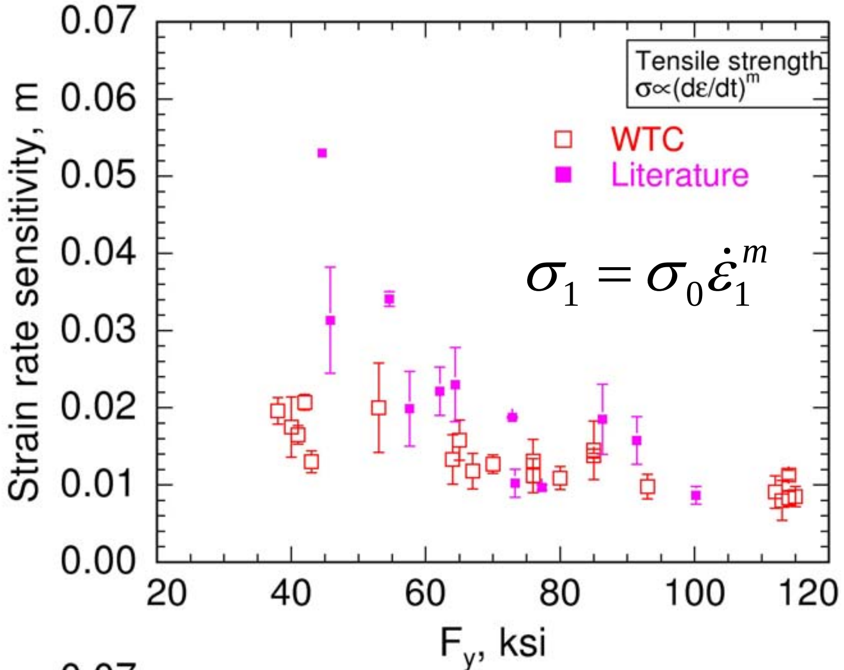
m = 0.02 results in 5 % stress increase per decade of strain rate

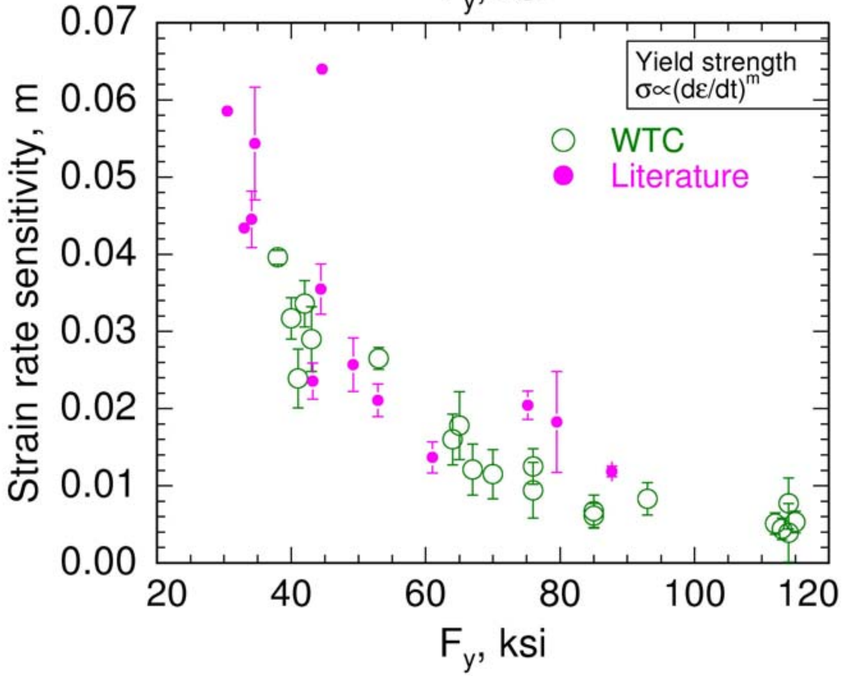






Properties: strain rate sensitivity-comparison with literature



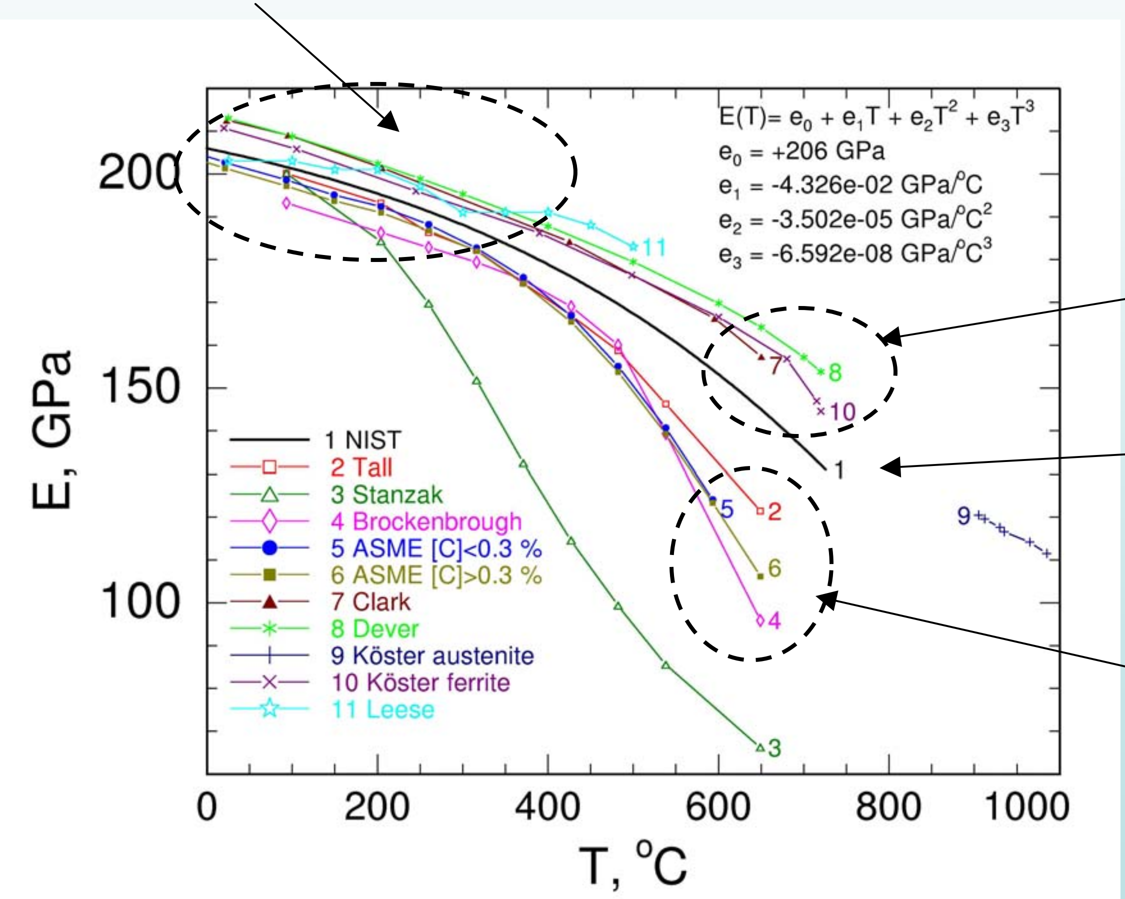


- WTC steels are similar to other low-carbon steels
- Data sources: low-carbon, low-alloy structural steels
- No literature data on specific construction steels (A 36, A 572, etc)

Properties: high-temperature elastic modulus

Wide variation in literature values!

Slopes near RT are all similar

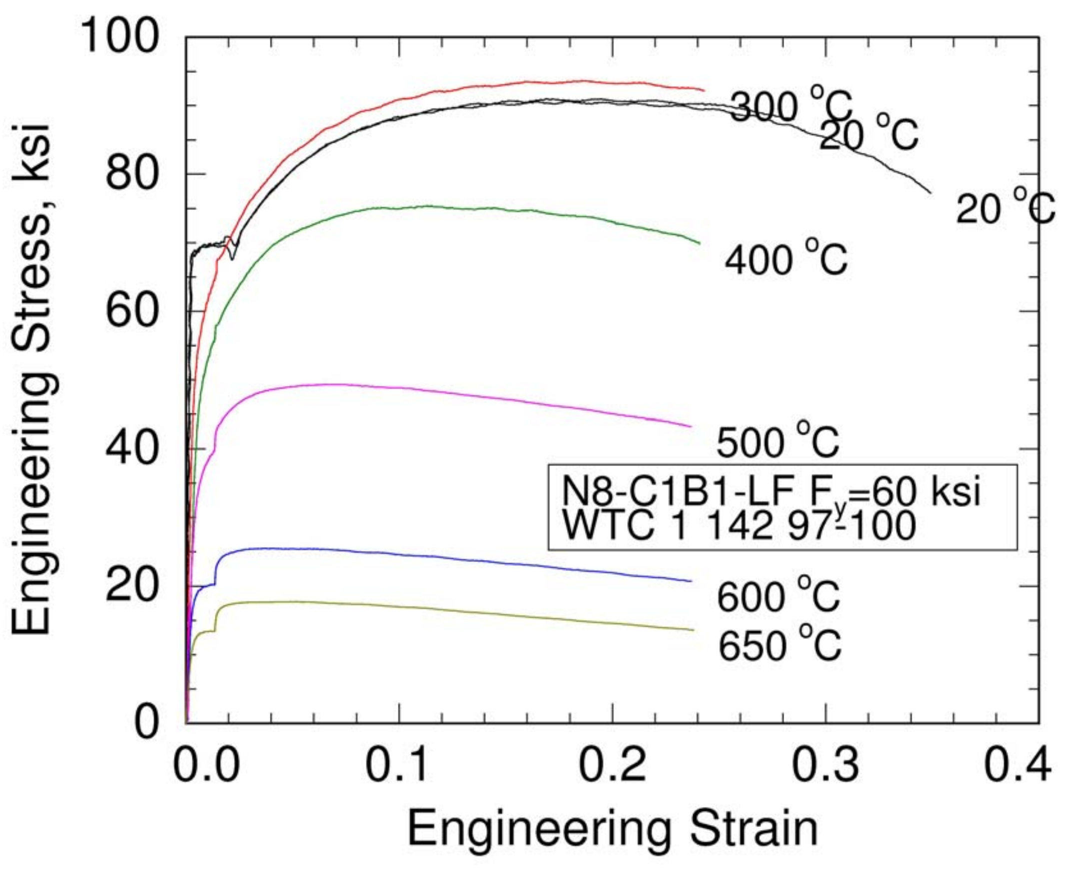


Ultrasonic determinations

NIST value determined using DMA @ 1hz. Recommended value independent of chemistry

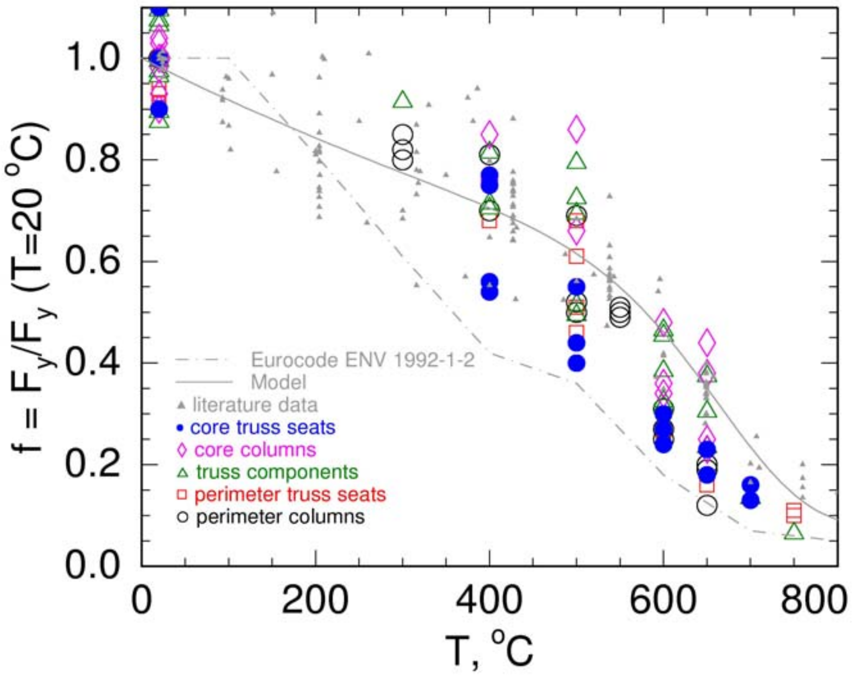
Determinations primarily from tension tests

Properties: high-temperature stress-strain behavior

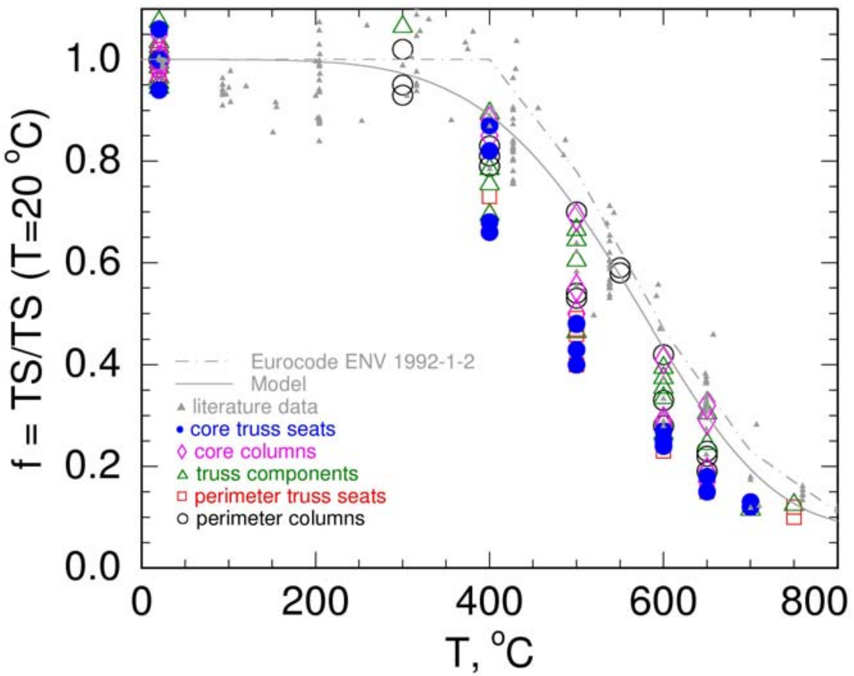


- Protocol: ASTM E 21
- 3 perimeter column steels: F_y=60 ksi, 100 ksi
- 2 WF core column steels F_y=36 ksi, 42 ksi
- 2 truss steels F_y=36 ksi, 60 ksi
- Limitations
  - Strain rate dependence of strength
  - Represents upper limit of strength

Properties: high-temperature yield and tensile strength



Yield strength



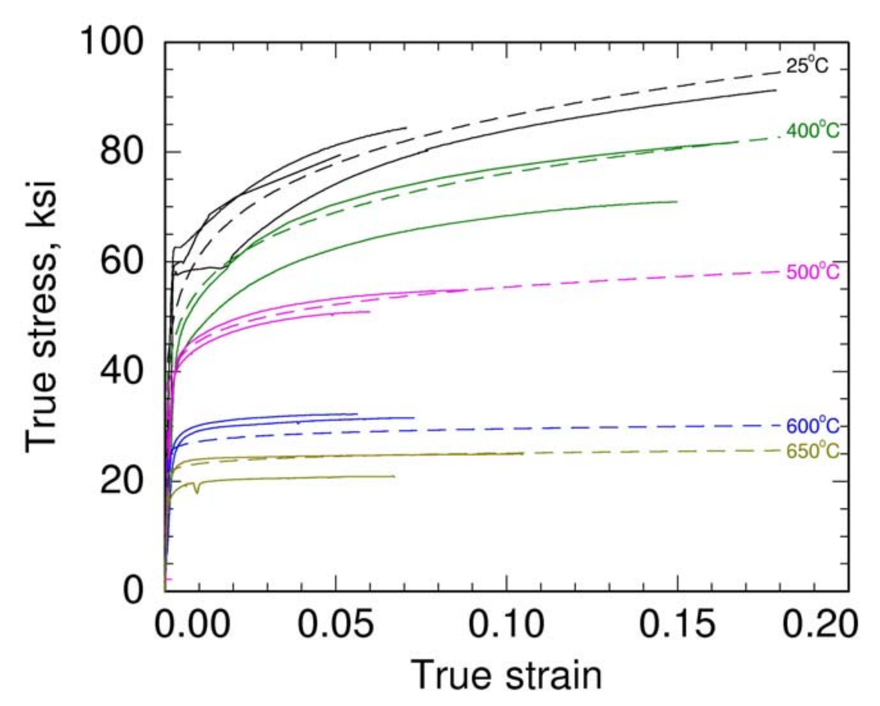
Tensile strength

- Model developed on literature data on 1960’s era steels
- Differences reflect (presumed) differences in test protocol
- Model curve is phenomenological only

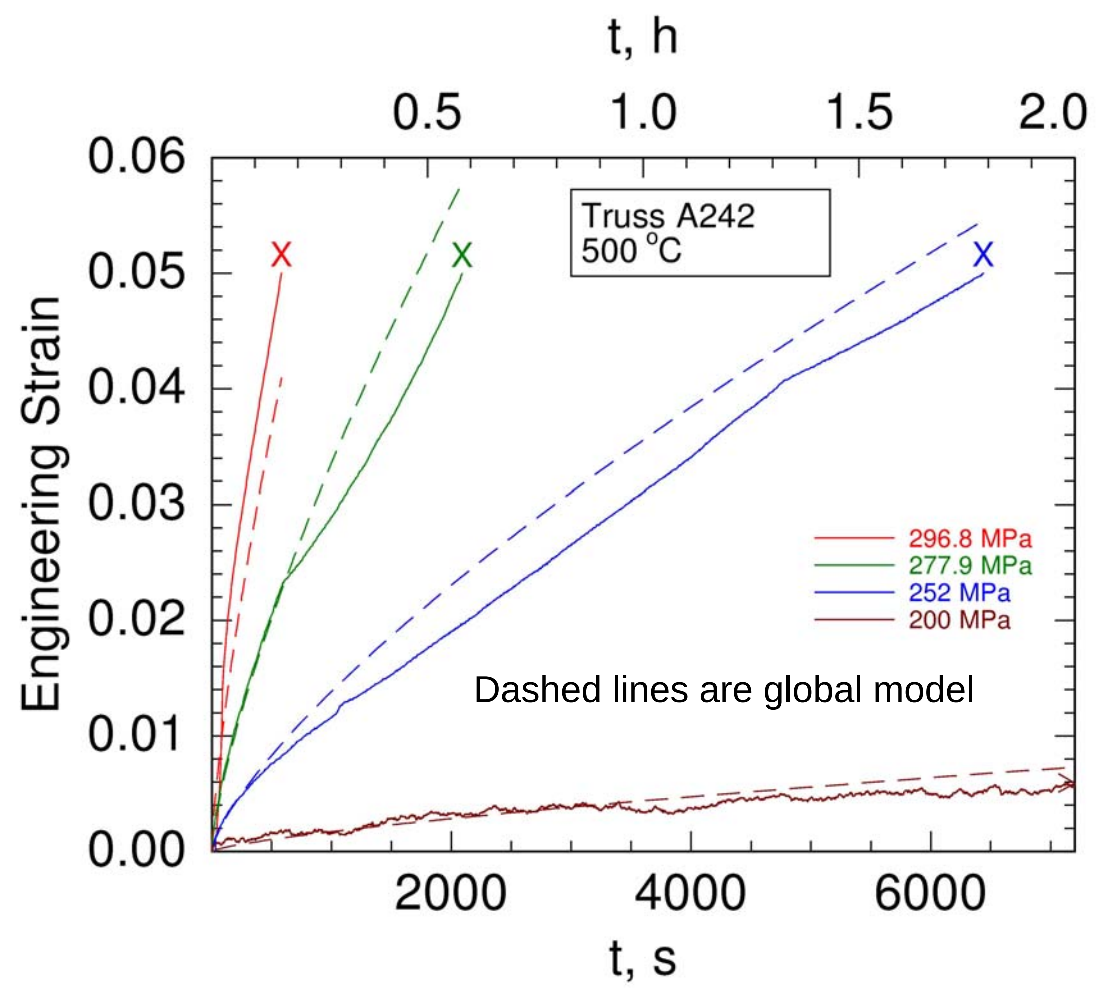
Properties: Modeling high-temperature stress-strain curves

- **Methodology**
  - Model steels with F_y=36 ksi using literature data for A 36 (Harmathy ‘70)
  - Model steels with F_y >36 ksi using NIST data for A 242 floor truss steel
  - Scale stress strain curves for untested steels by ratios of RT tensile strengths, RTS
- **Results**
  - Method accounts for change in work hardening
  - Represents upper limit or strength

$$\sigma = R_{TS} K(T) \varepsilon^{n(T)}$$



Properties: Creep



- Methodology
  - Characterize floor truss steels
  - 0 h < *t* < 2 h
  - Model all other steels using literature values for AS A149 (like A 36)
  - Scale applied stress by ratio of RT tensile strengths (best method)

Floor truss steels:

$$\varepsilon_c = At^b\sigma^C$$

$$A(T) = \exp(A_0 + A_1T + A_2T^2)$$

$$B(T) = B_0 + B_1T^{B_2}$$

$$C(T) = C_0 + C_1T$$

All other steels:

$$\varepsilon_c = At^b\sigma^C$$

$$A(T) = \exp(A_0 + A_1T)$$

$$B(T) = B_0 + B_1T$$

$$C(T) = C_0 + C_1T$$

Part IV

Failure analysis to constrain output of models

Damage and Failure Analysis

Purpose:

- To provide input material data for the impact model (D-BT)
- To validate impact model with exterior wall failure mode observations
- To provide insights into collapse mechanisms
- To assess adhesion of SFRM after impact
- To determine what temperature was experienced by components

Evidence available:

- Recovered steel components (structural and metallurgical aspects)
- Photographic and video

Challenges:

- Ambiguity as to when damage happened (impact, collapse or post-collapse)
- Sample degradation
- Sample identification

Exterior Steel Damage Due to Aircraft Impact

Original Image – North Tower, North Face

© 2001. Roberto Rabanne/CORBIS

Processed Image

© 2001. Roberto Rabanne/CORBIS

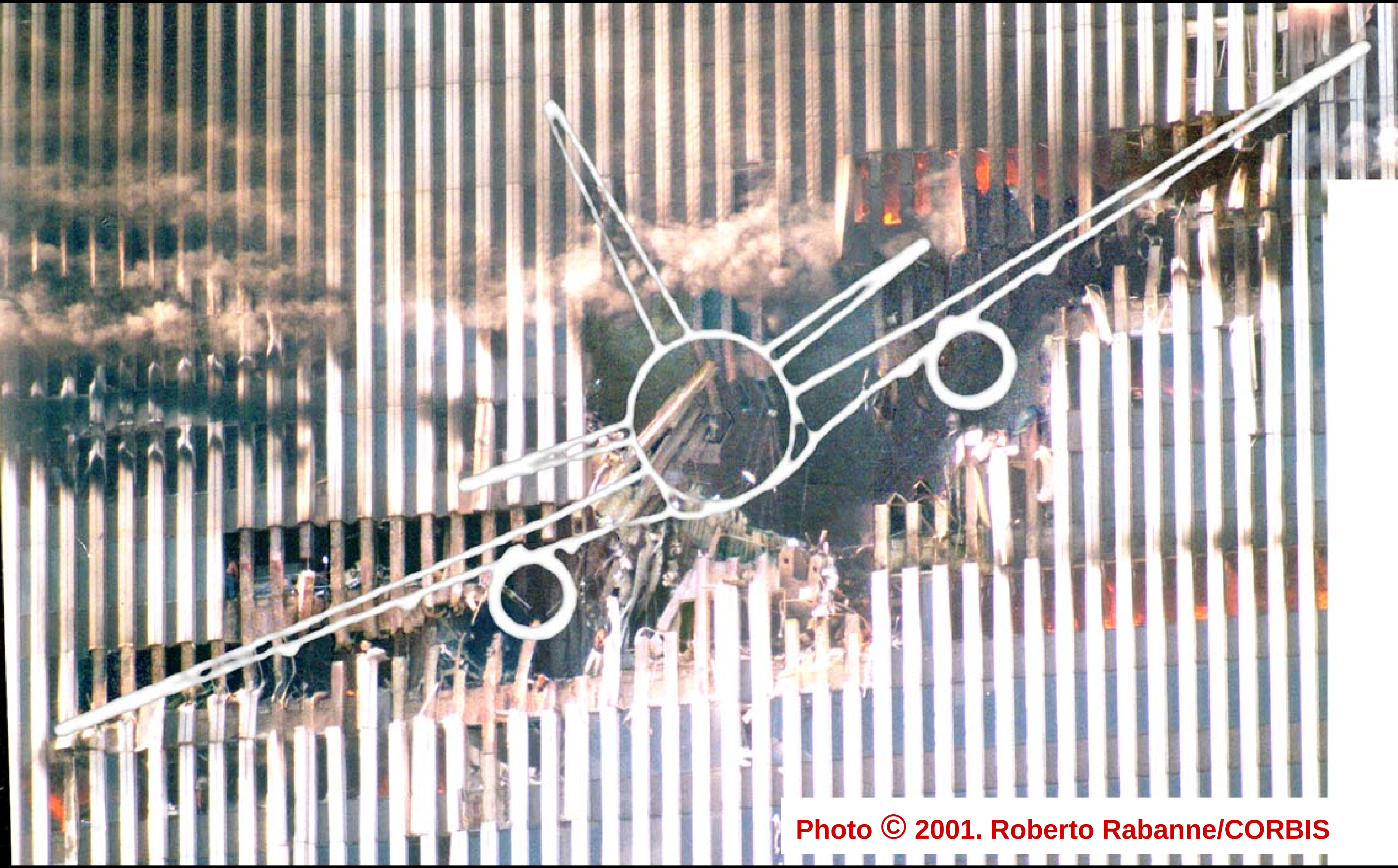


Photo © 2001. Roberto Rabanne/CORBIS

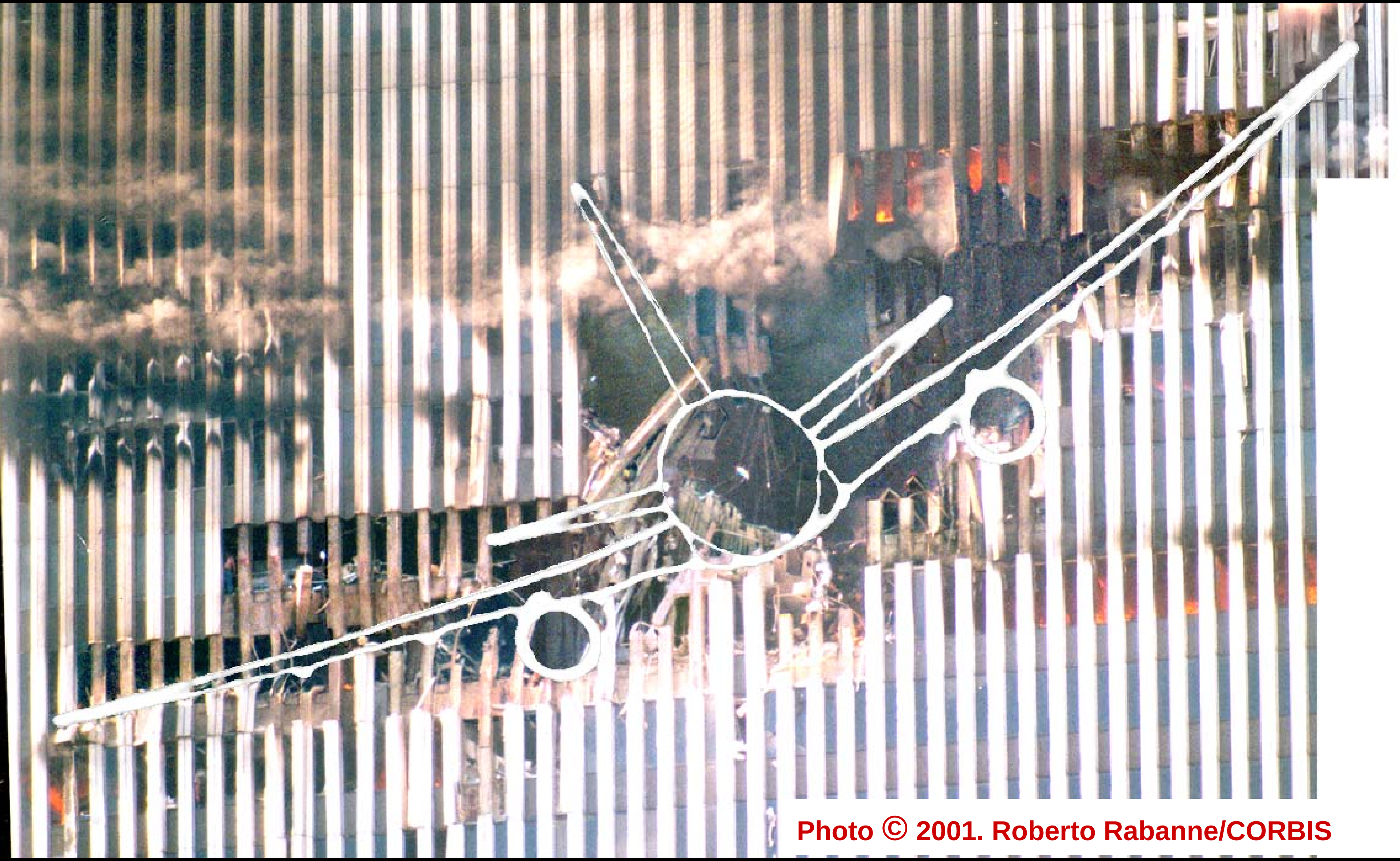


Photo © 2001. Roberto Rabanne/CORBIS

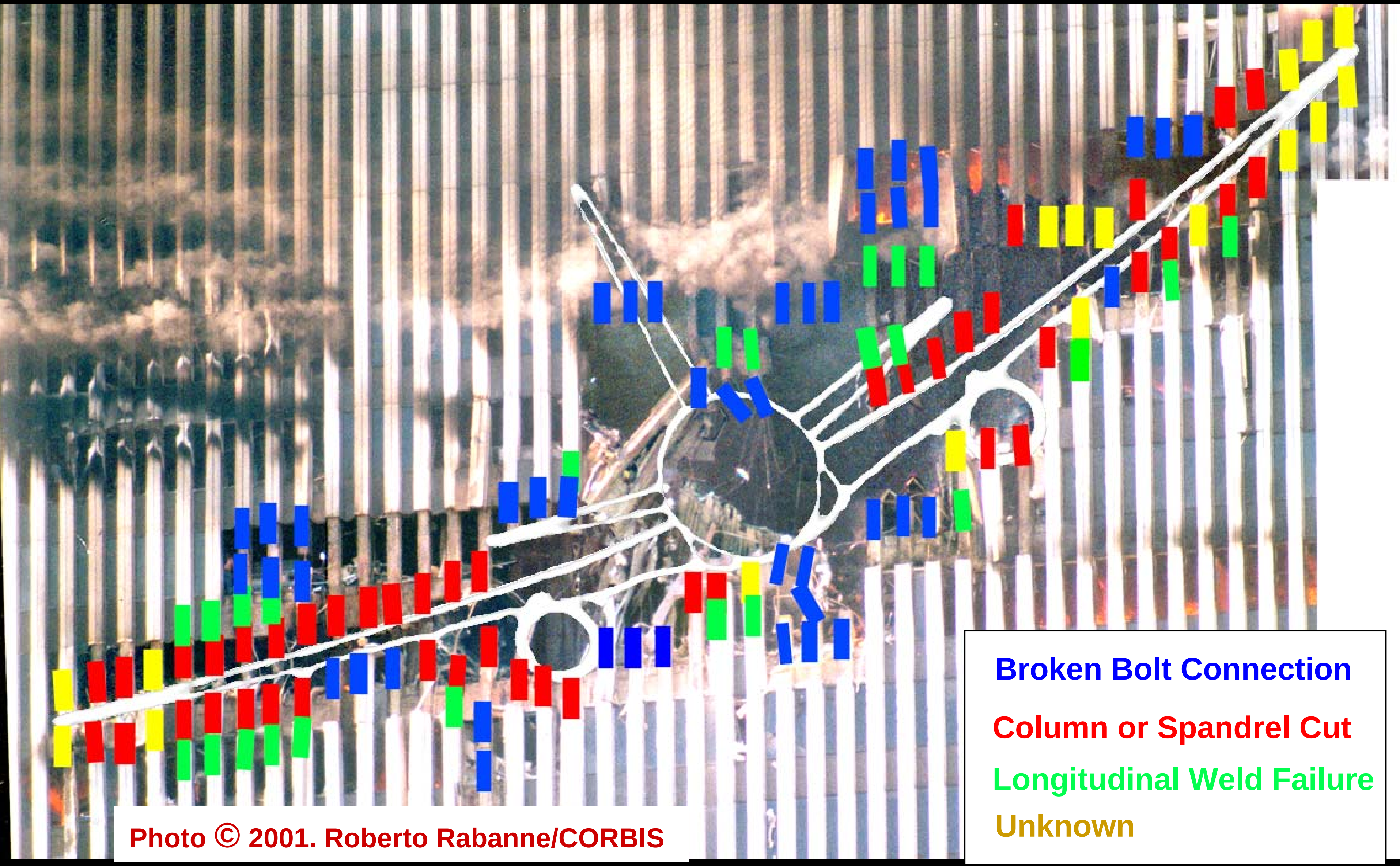
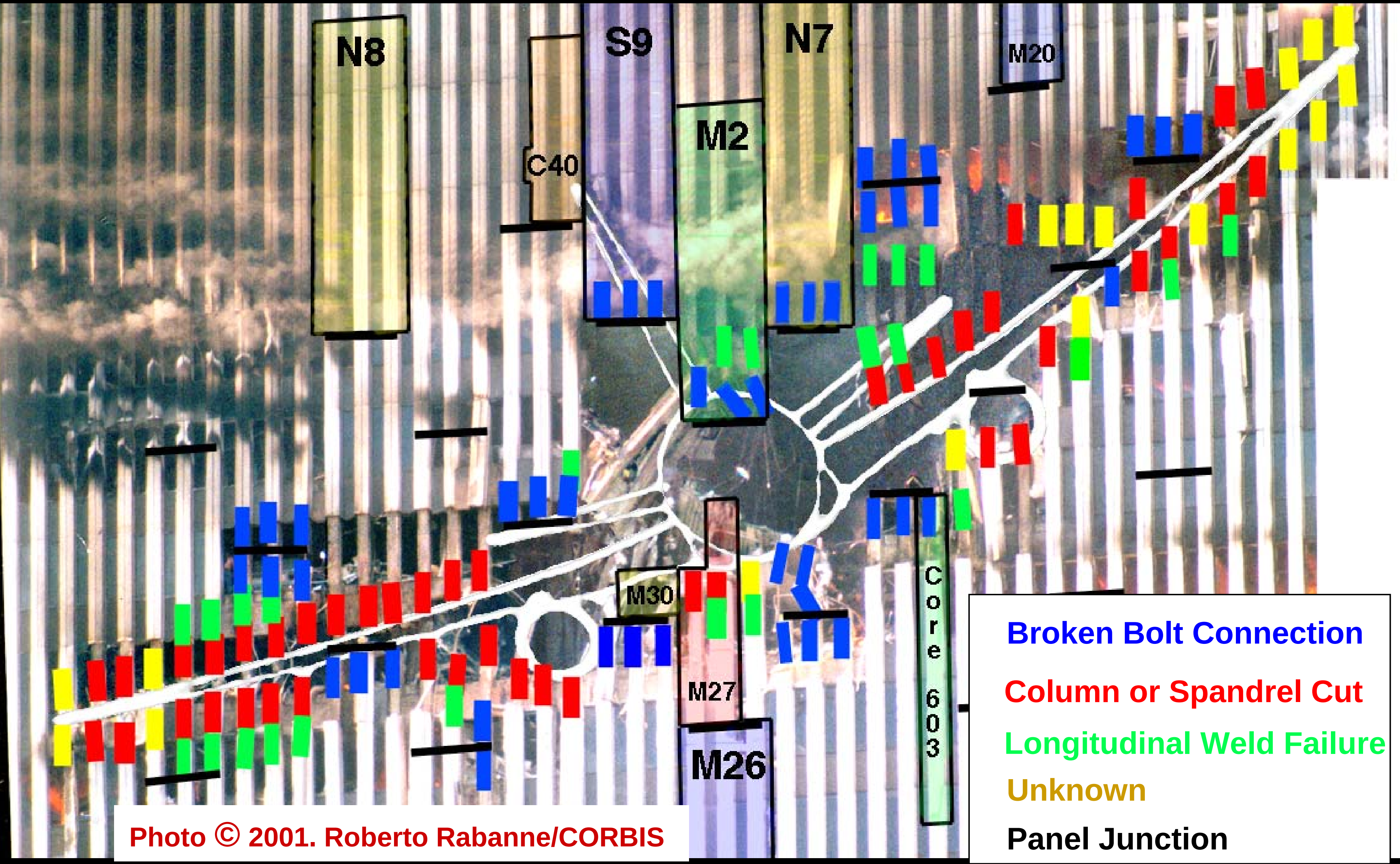


Photo © 2001. Roberto Rabanne/CORBIS

Identified failures



Broken Bolt Connection

Column or Spandrel Cut

Longitudinal Weld Failure

Unknown

Panel Junction

Photo © 2001. Roberto Rabanne/CORBIS

Original locations of inventory panels as identified by Metallurgy Division

WTC 1, North Face

Photo © 2001. Roberto Rabanne/CORBIS

M-27

Photo © 2001. Roberto Rabanne/CORBIS

Direct comparison with state of recovered steel

C40 hit by tip of tail?

Closer examination shows collision damage unlikely – damage occurred during fall

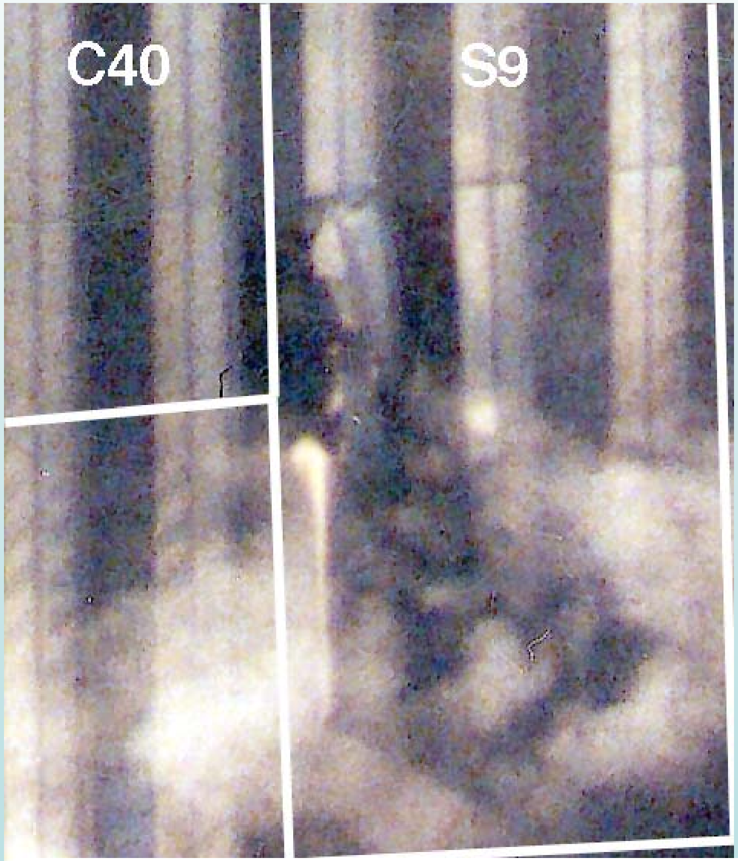
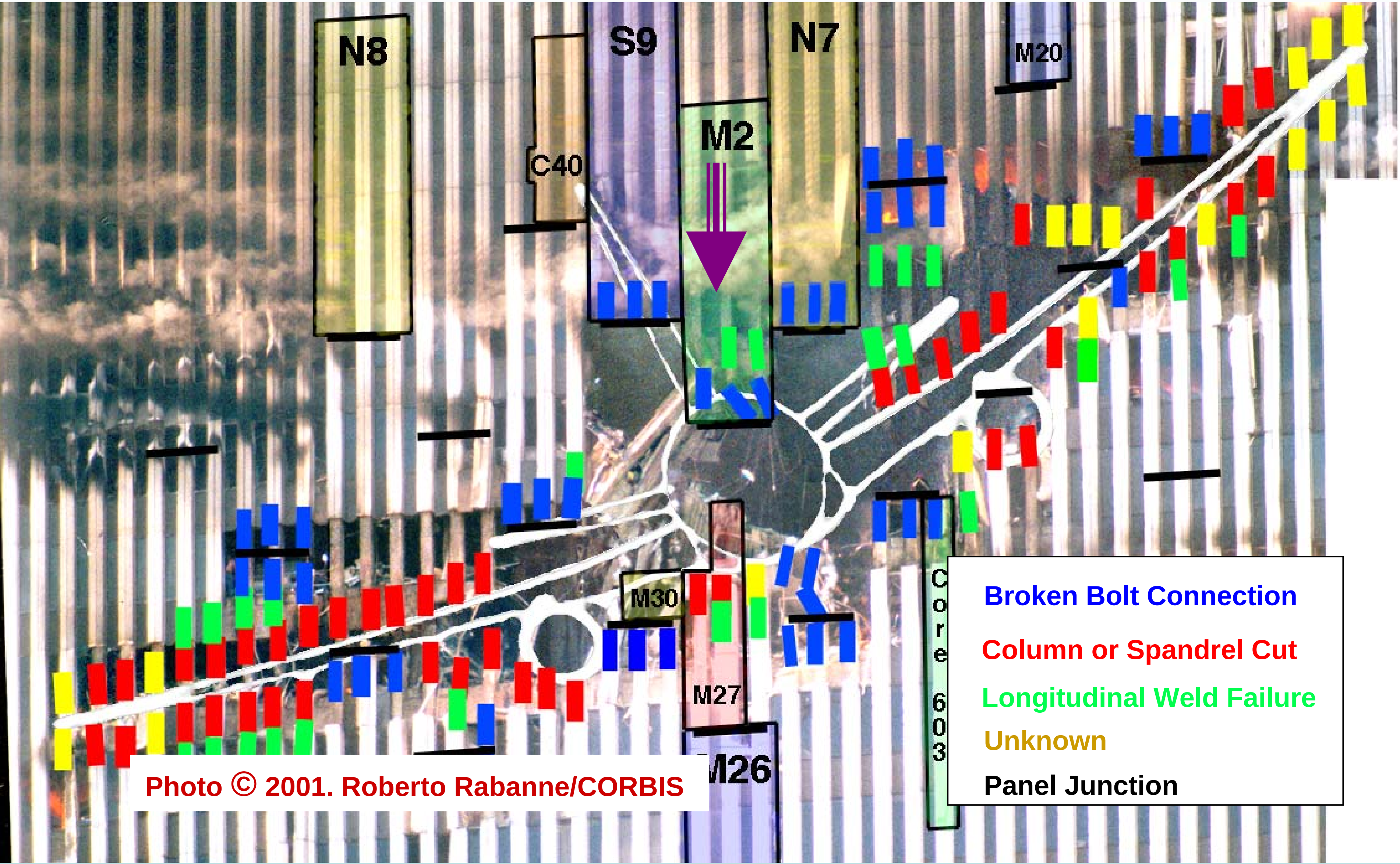


Photo © 2001. Roberto Rabanne/CORBIS

Type of fracture of perimeter steel



🟦 Broken Bolt Connection

🟥 Column or Spandrel Cut

🟩 Longitudinal Weld Failure

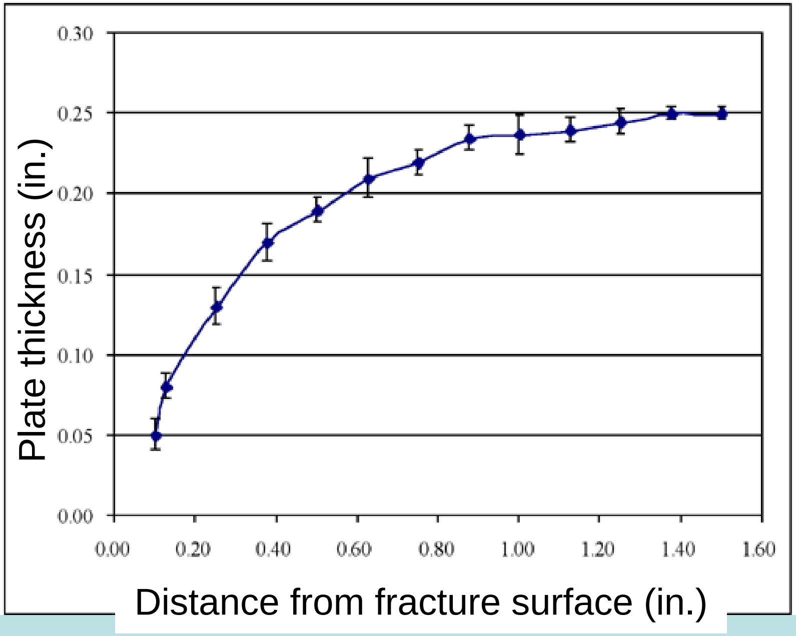
🟨 Unknown

▬ Panel Junction

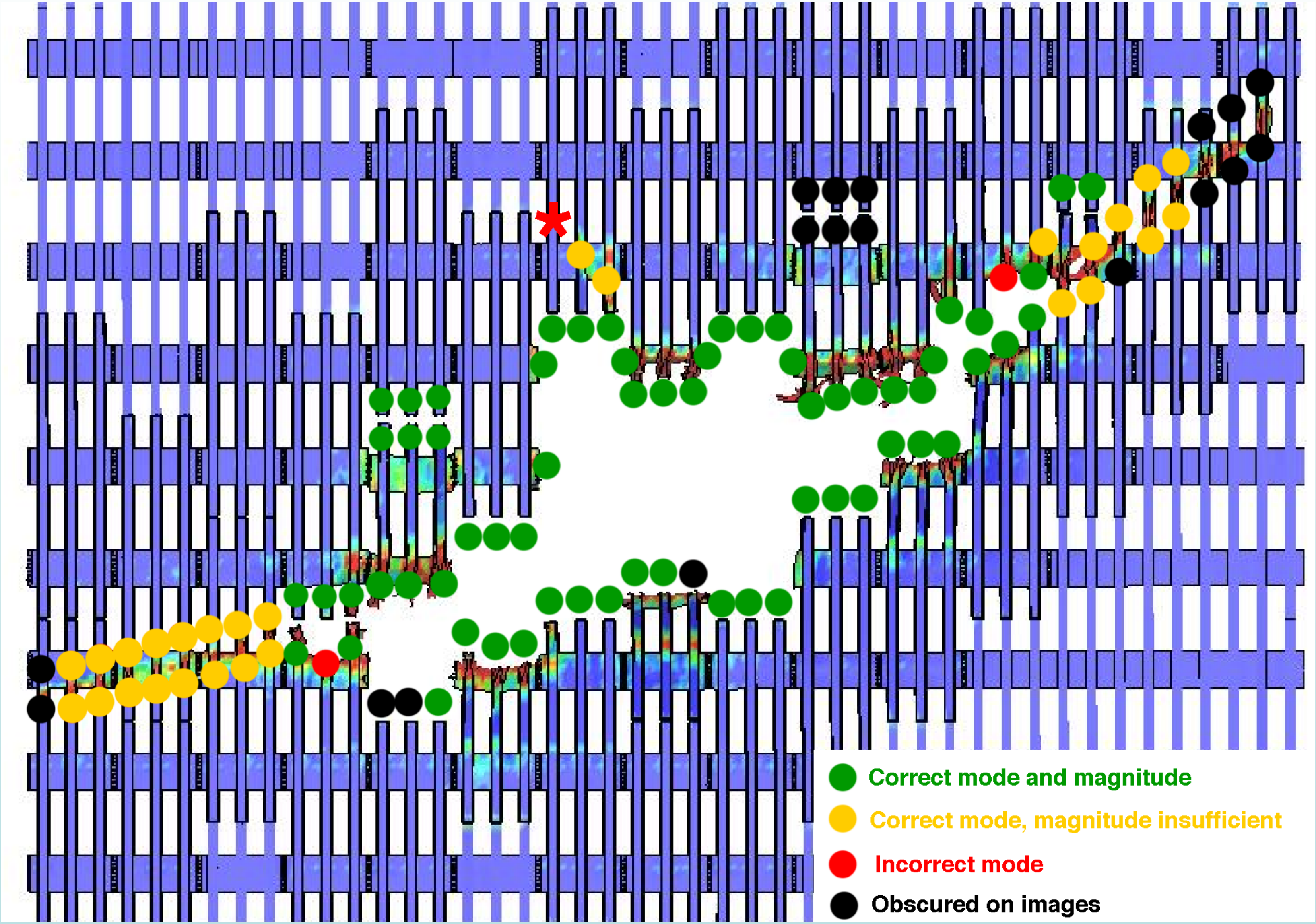
Photo © 2001. Roberto Rabanne/CORBIS

High Rate Failure Mode Observation

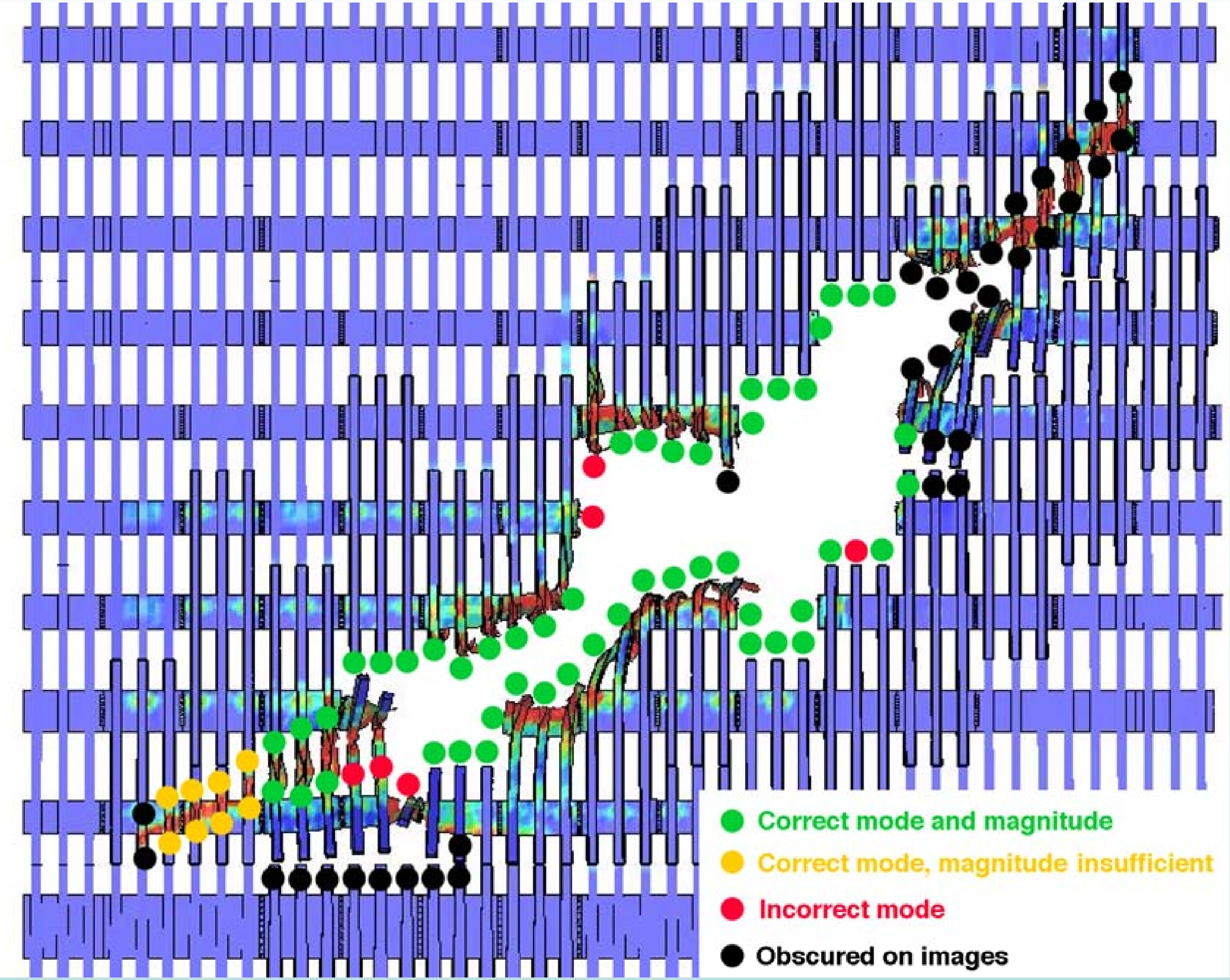
- Measured fracture surface profile on outer web from M2 that broke in the impact
- Considerable thinning within an inch of the fracture surface
- Indicates large energy absorption during failure
- No need to have a transition from a low energy to high energy absorption failure mode in the FEA model of the aircraft impact with the building.



Validation of Aircraft Impact Model Prediction With Observations for WTC 1

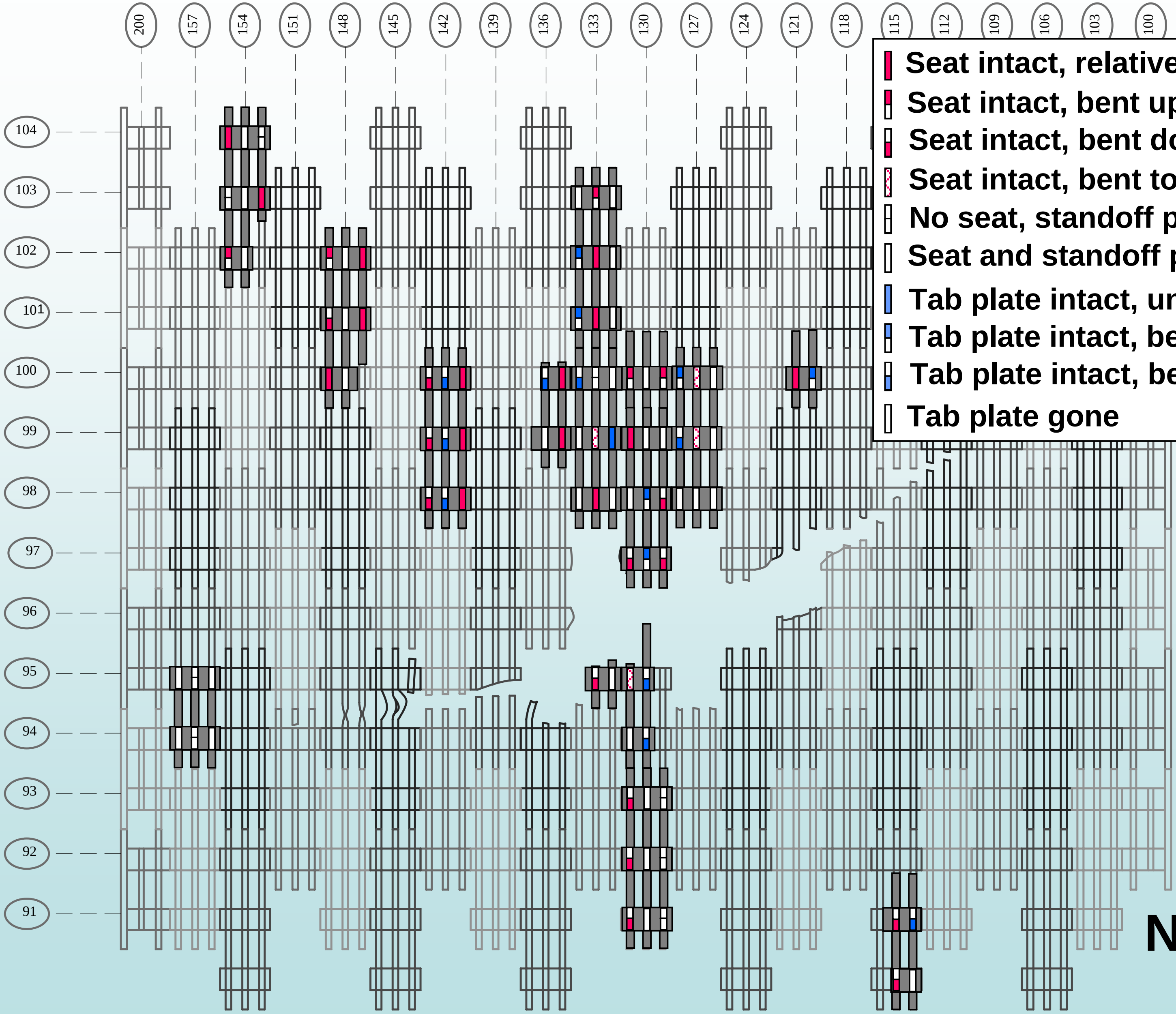


Validation of Aircraft Impact Model Prediction With Observations for WTC 2



Evidence of Collapse Mechanisms From Examination of Recovered Steel

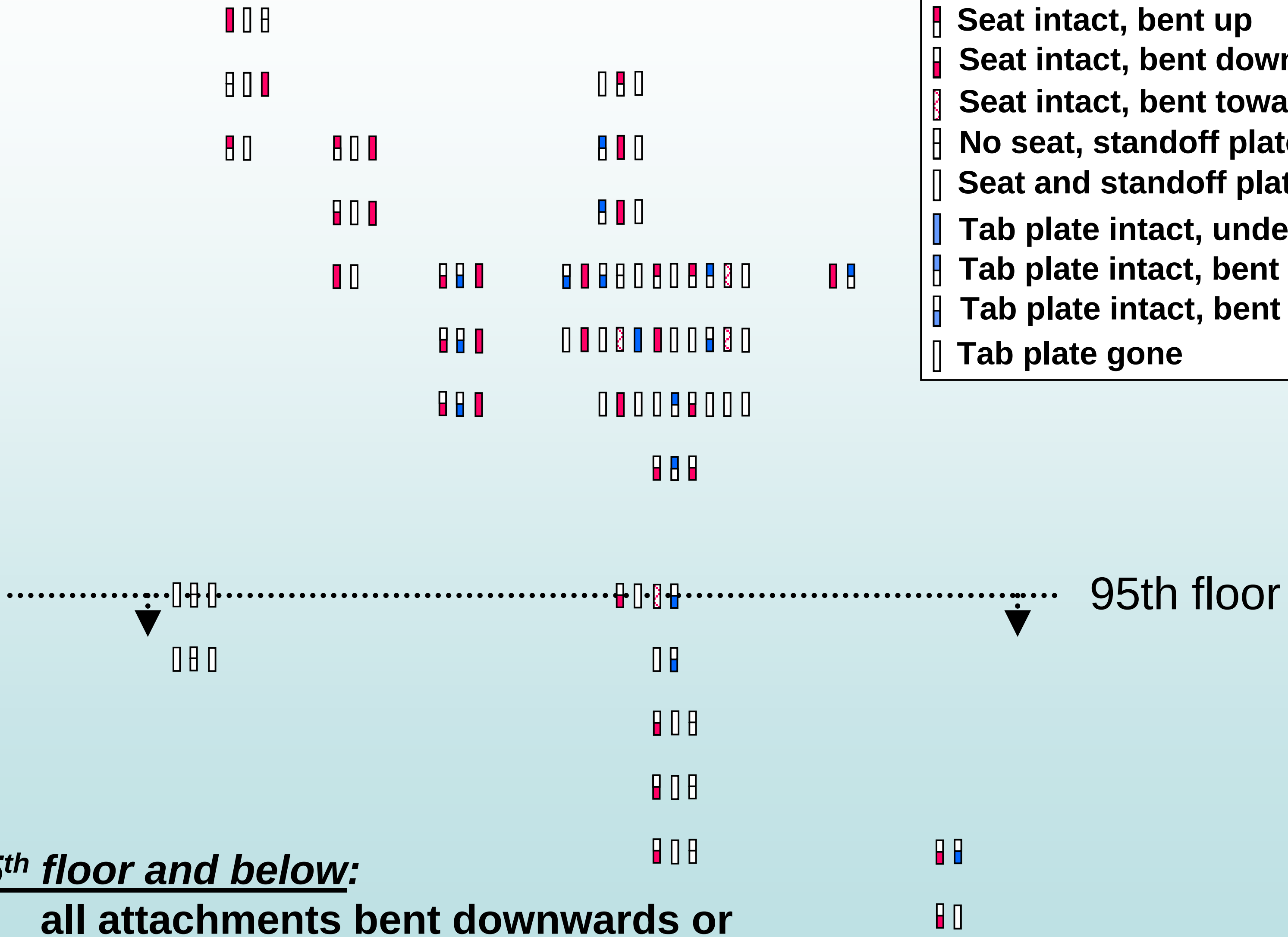
Floor Truss Support: Perimeter Seat Damage



- 🟥 Seat intact, relatively undeformed
- 🟥 Seat intact, bent up
- 🟥 Seat intact, bent down
- ▨ Seat intact, bent towards column
- ☐ No seat, standoff plate remains
- ☐ Seat and standoff plates gone
- 🟦 Tab plate intact, undeformed
- 🟦 Tab plate intact, bent up
- 🟦 Tab plate intact, bent down
- ☐ Tab plate gone

WTC 1
North Face

Floor Truss Support: Perimeter Seat Damage



- **Seat intact, relatively undeformed**
- **Seat intact, bent up**
- **Seat intact, bent down**
- **Seat intact, bent towards column**
- **No seat, standoff plate remains**
- **Seat and standoff plates gone**
- **Tab plate intact, undeformed**
- **Tab plate intact, bent up**
- **Tab plate intact, bent down**
- **Tab plate gone**

<u>95th floor and below</u>:

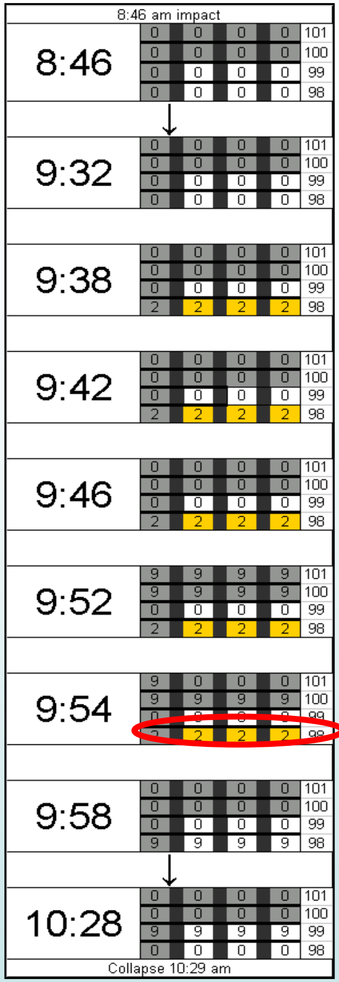
all attachments bent downwards or missing (components ripped off at welds)

Evidence of Maximum Temperature Reached by Components From Examination of Recovered Steel

Methods to Determine High Temperature Excursions of Steel

- Microstructural changes
- Calibrated stress relief of welds
- Thermal analysis of metastable weld phases
- Annealing of hardened bolts and washers
- Degradation of paint

Each approach was examined. Microstructural analysis and condition of the paint provided useful information



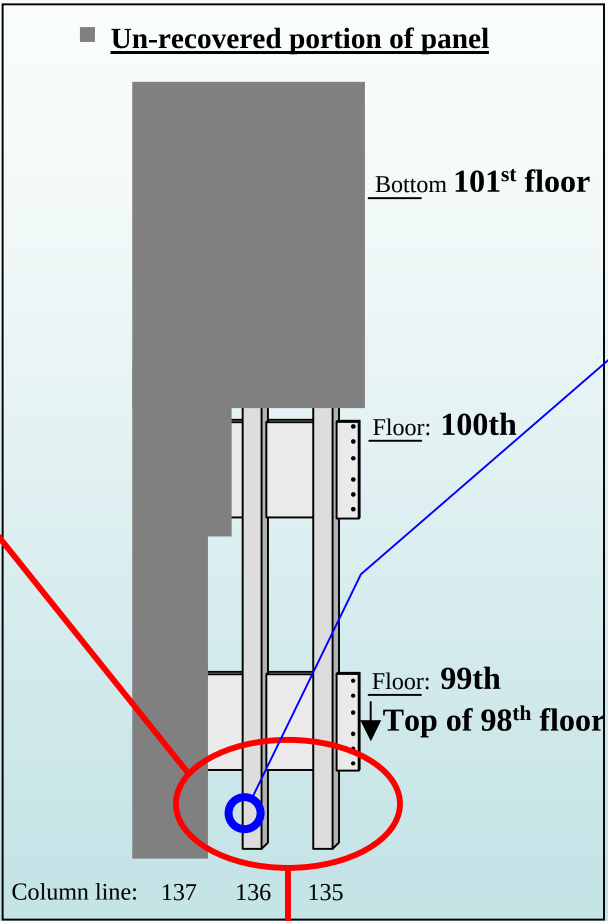
8:46 am impact

8:46	0	0	0	0	101
	0	0	0	0	100
	0	0	0	0	99
	0	0	0	0	98
9:32	0	0	0	0	101
	0	0	0	0	100
	0	0	0	0	99
	0	0	0	0	98
9:38	0	0	0	0	101
	0	0	0	0	100
	0	0	0	0	99
	2	2	2	2	98
9:42	0	0	0	0	101
	0	0	0	0	100
	0	0	0	0	99
	2	2	2	2	98
9:46	0	0	0	0	101
	0	0	0	0	100
	0	0	0	0	99
	2	2	2	2	98
9:52	9	9	9	9	101
	9	9	9	9	100
	0	0	0	0	99
	2	2	2	2	98
9:54	9	0	0	0	101
	9	9	9	9	100
	0	0	0	0	99
	2	2	2	2	98
9:58	0	0	0	0	101
	0	0	0	0	100
	0	0	0	0	99
	9	9	9	9	98
10:28	0	0	0	0	101
	0	0	0	0	100
	9	9	9	9	99
	0	0	0	0	98

Collapse 10:29 am

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

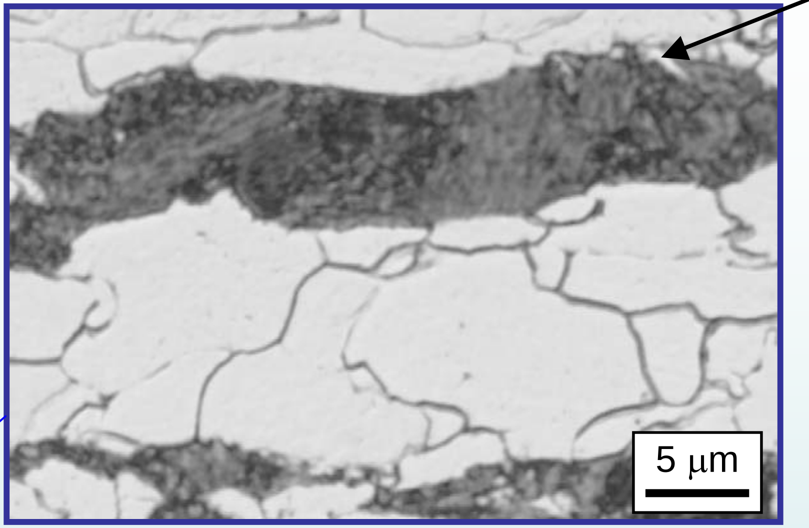
NIST Name:	C-40
Panel ID:	A136: 98-101
Panel location:	WTC 1, north face
Window lines:	34-37



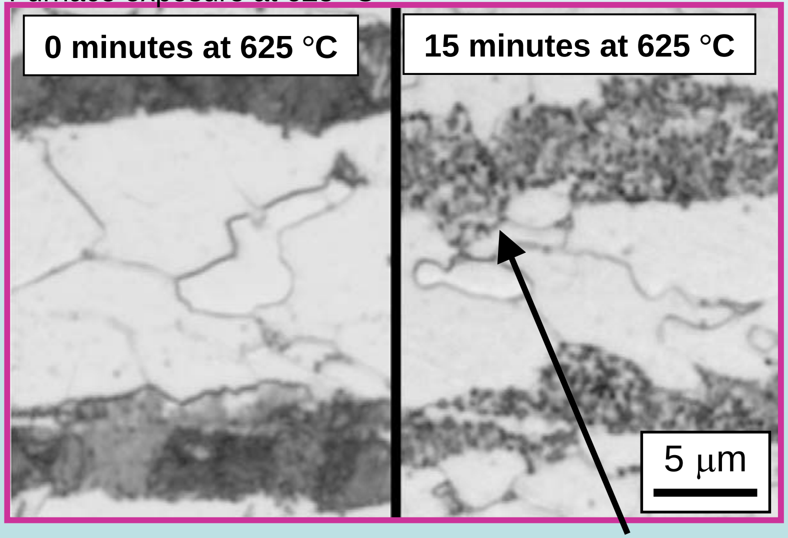
fire exposure:
16 minutes minimum

Steel sample: WTC1, col 136, 98th floor
-Column with Fy = 60 ksi
-No mud cracking of paint

Cementite as *plates*



Laboratory exposed sample: WTC1, col 126, 97th fl
- Similar column with Fy = 60 ksi, no mud cracking
- Furnace exposure at **625** °C



Cementite has begun to *spheroidize* after 15 min exposure

Summary of metallographic analysis – Perimeter and Core Columns

For all perimeter column flanges, outer webs, and spandrels with Fy < 75 ksi (controlled rolled)

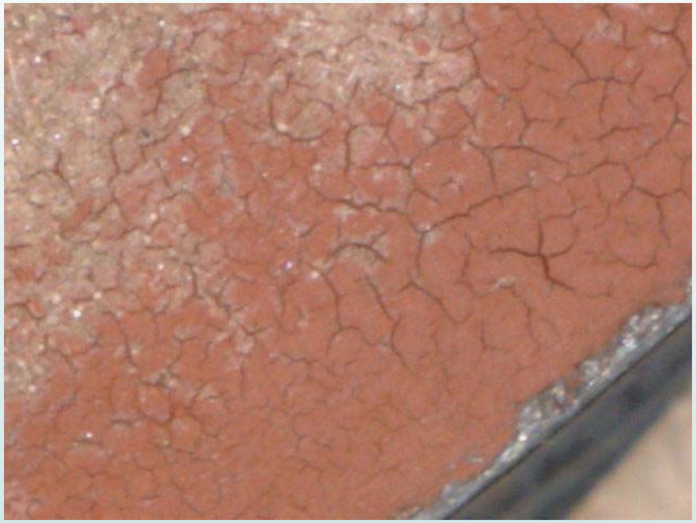
- 136 distinct samples (many from the fire floors) evaluated with no spheroidization observed, and thus no steel temperatures over 625 °C for significant time.

Caveats

- samples represent < 3% of columns in fire zone
- samples represent < 1% of columns in the buildings

“Paint” is actually a ceramic coating

- Mostly Fe- and Ti- oxides with silica sand
- Applied at fabricator to prevent rust
- Tnemic 99



As applied

- Suspending liquid - high vapor pressure
- Bake cycle to dry out - 200 degrees F
- Left faint, closed drying cracks
- Almost no organics left to “burn”

After 250 degrees C for 1 hour

- “Mudcrack” pattern
- Roughly symmetrical in shape
- Caused by different thermal

expansion of paint and steel

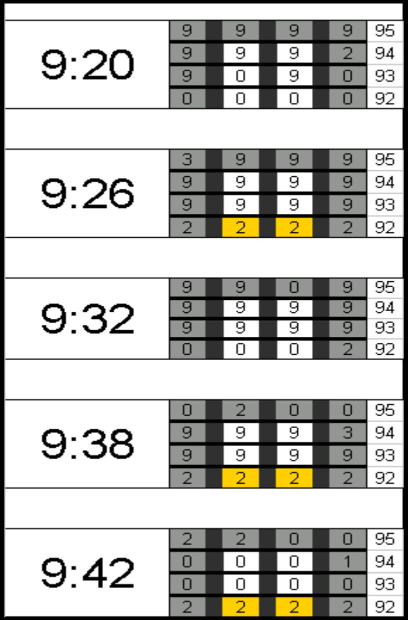
Important: The Paint Test is a *Negative* Test

The *absence* of cracking of the paint shows that the steel underneath did not reach 250 degrees C

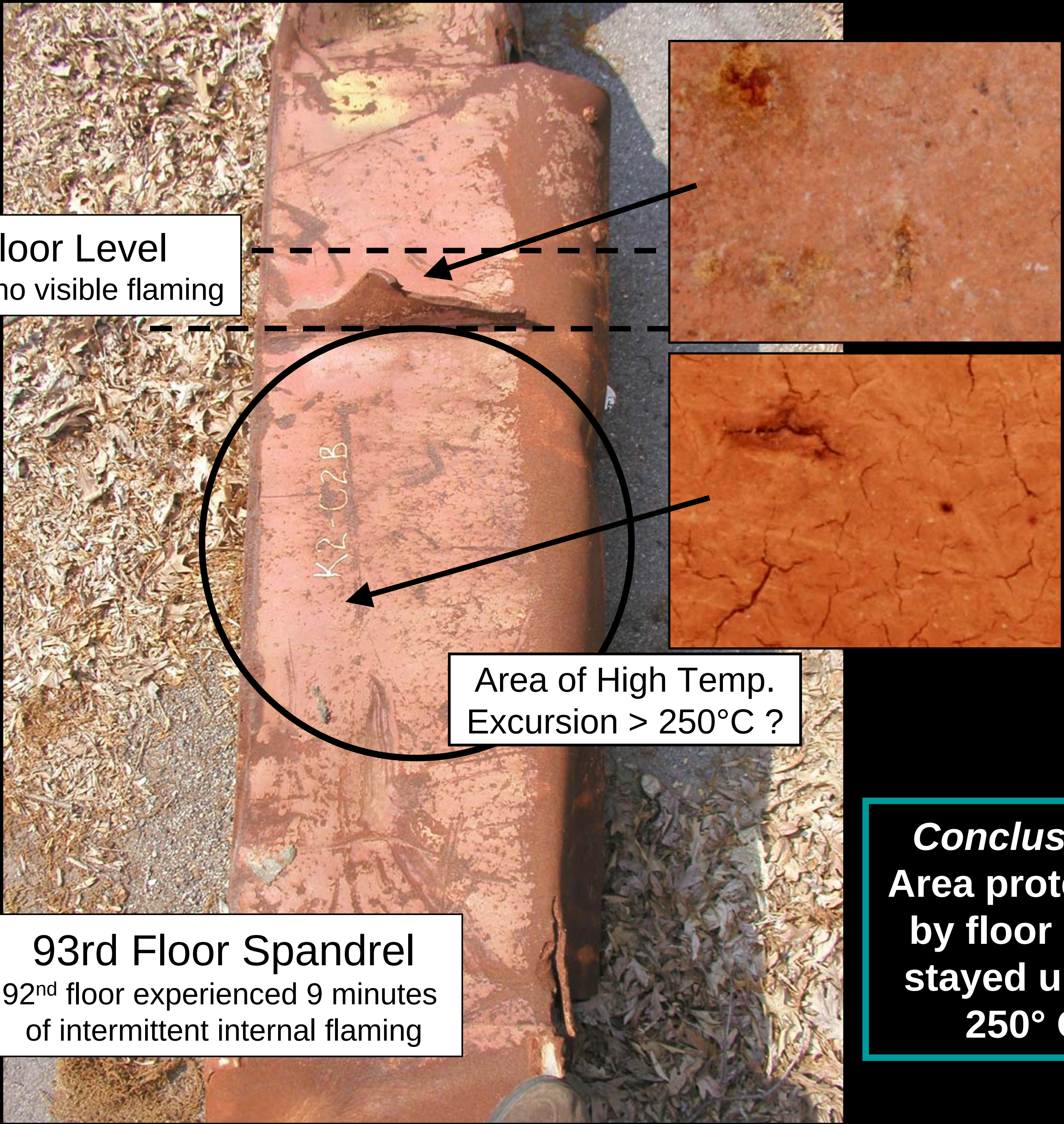
The *presence* of cracking means that one or more things happened:

- The steel underneath the paint exceeded 250 degrees C
- The steel underneath was plastically deformed (bent or stretched)
- The steel underneath corroded

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



93rd Floor Level

93rd floor – no visible flaming

Area of High Temp.
Excursion > 250°C ?

93rd Floor Spandrel

92nd floor experienced 9 minutes of intermittent internal flaming

Conclusion:

Area protected by floor slab stayed under 250° C

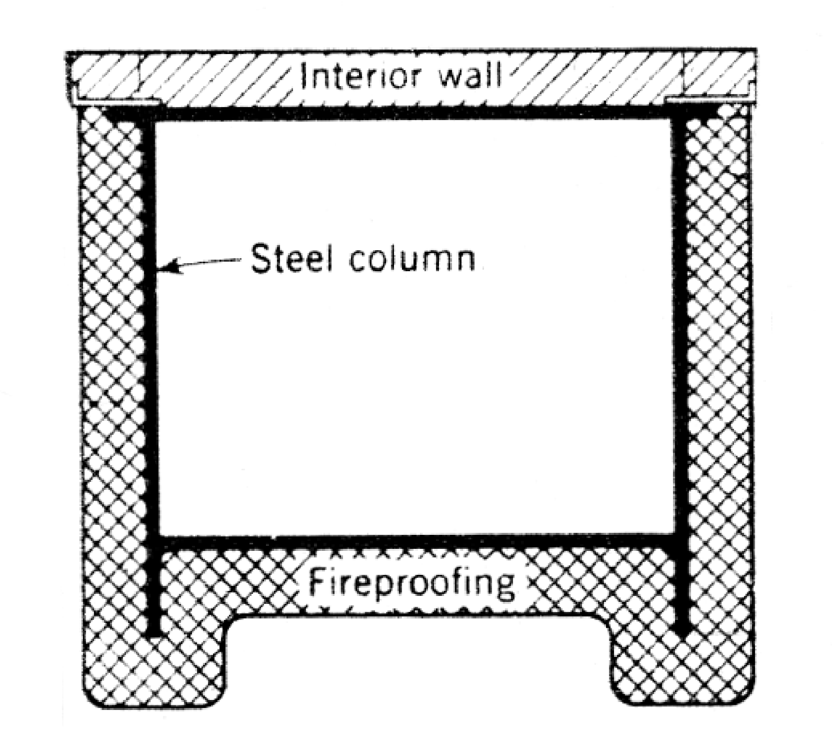
Paint Test Results:

- Paint was examined on all identified columns where fire was seen in windows
- Paint condition was used to map upper limits of temperature exposure
- Few perimeter panels (3 of 160 locations mapped) saw T > 250 °C

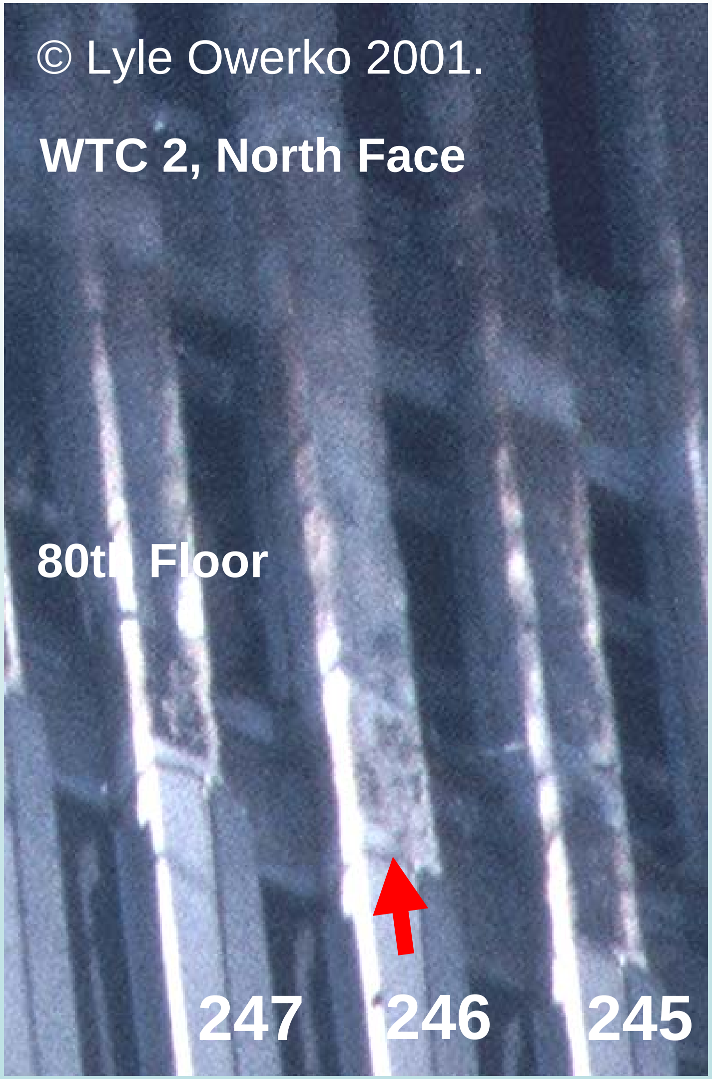
  Caveat - samples represent < 3% of columns in fire zone
- Core columns not characterized due to lack of intact paint on identified specimens
- Information provided to fire modelers

Damage to SFRM on Exterior Columns

Application of SFRM to External Columns

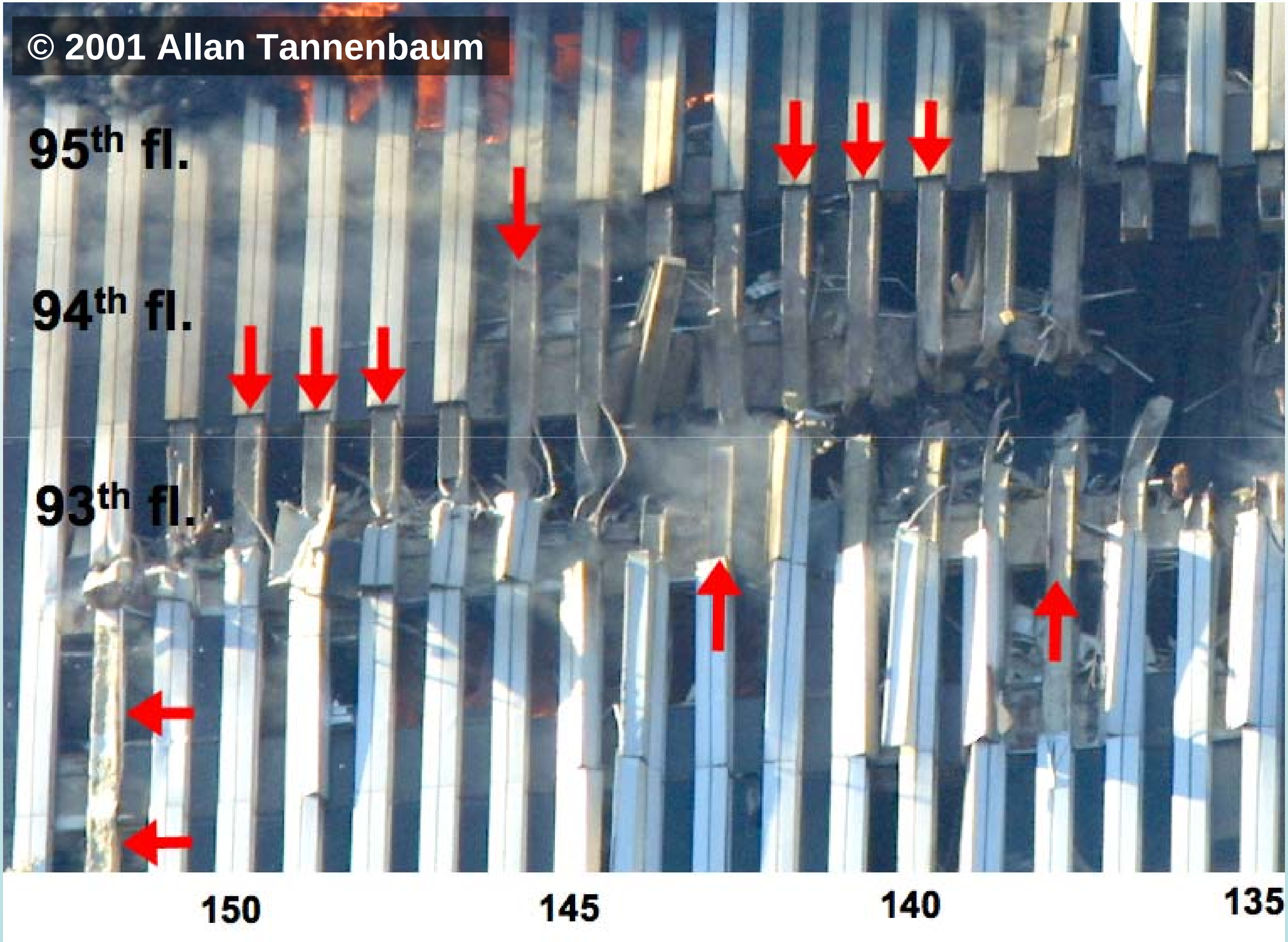


- By design, uniform thickness
    - As applied, region between flange ends filled (for example, see column 246 at right)
- Missing SFRM from outer flange indicated by shadowing and exposed red paint



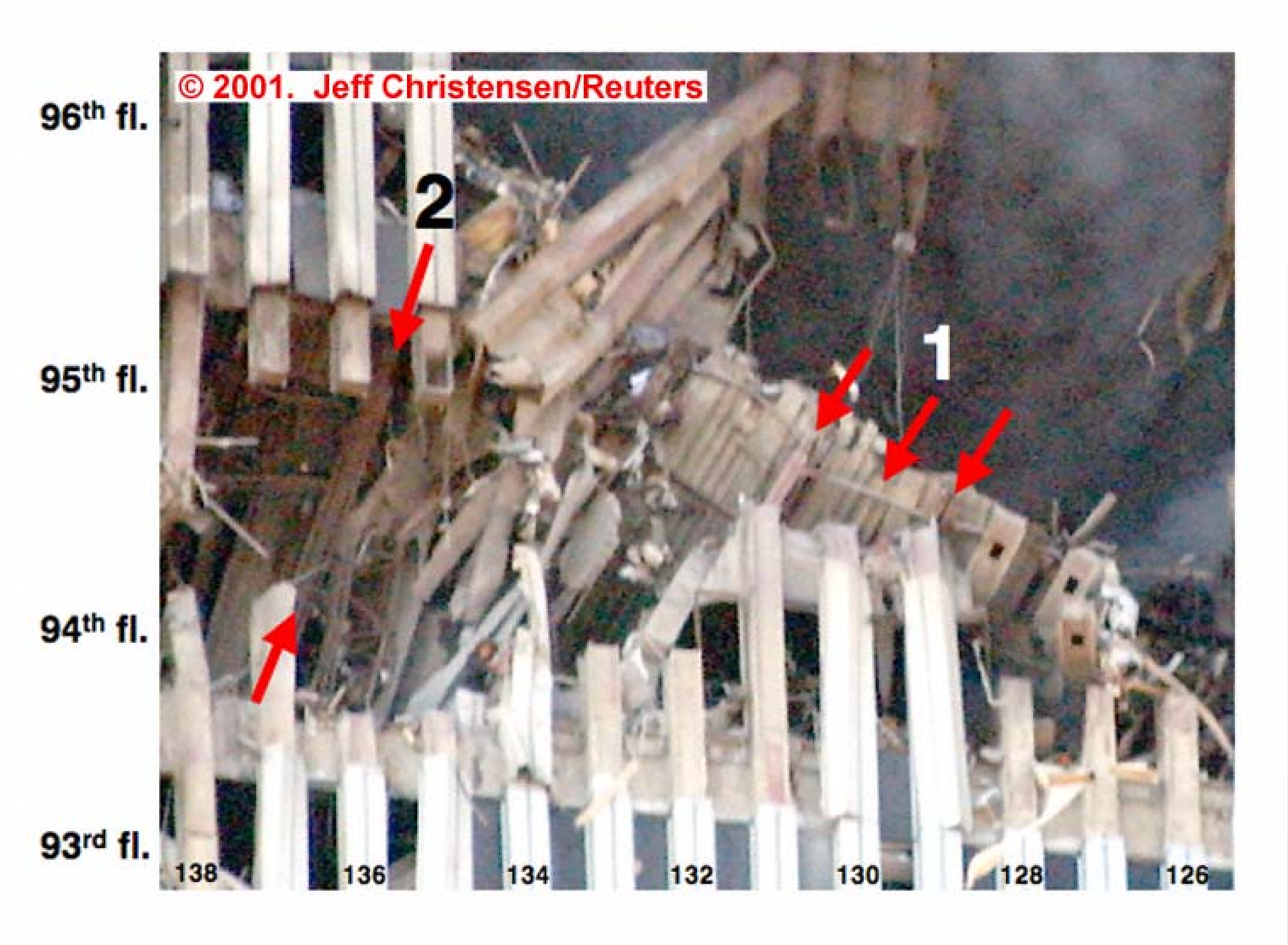
Direct Impact

North Face of WTC1 - Left Side of Impact Hole

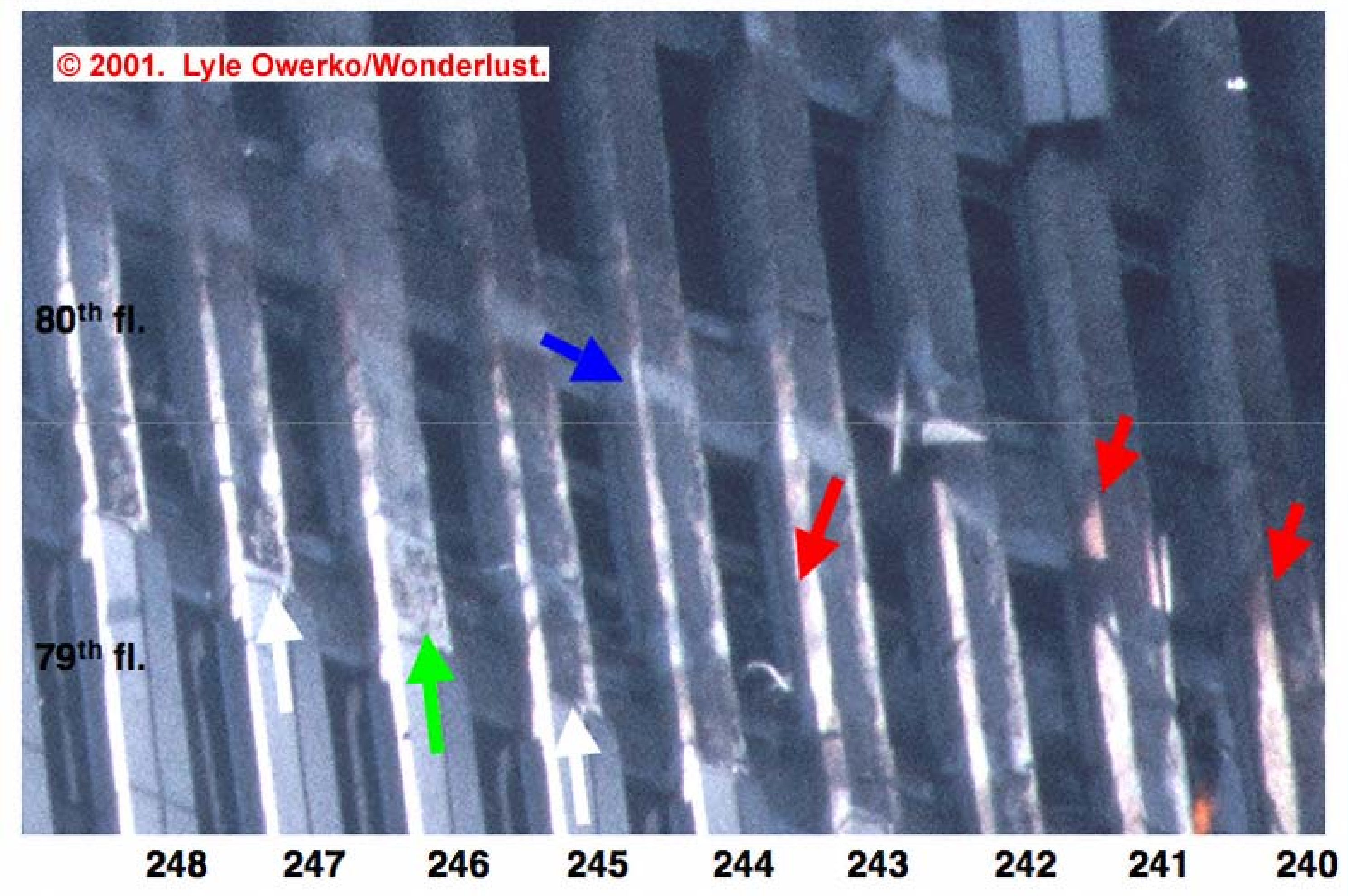


Direct Impact

North Face of WTC1: SFRM Missing from Trusses



Internal Impact
North Face of WTC 2



Removed from flanges (red)

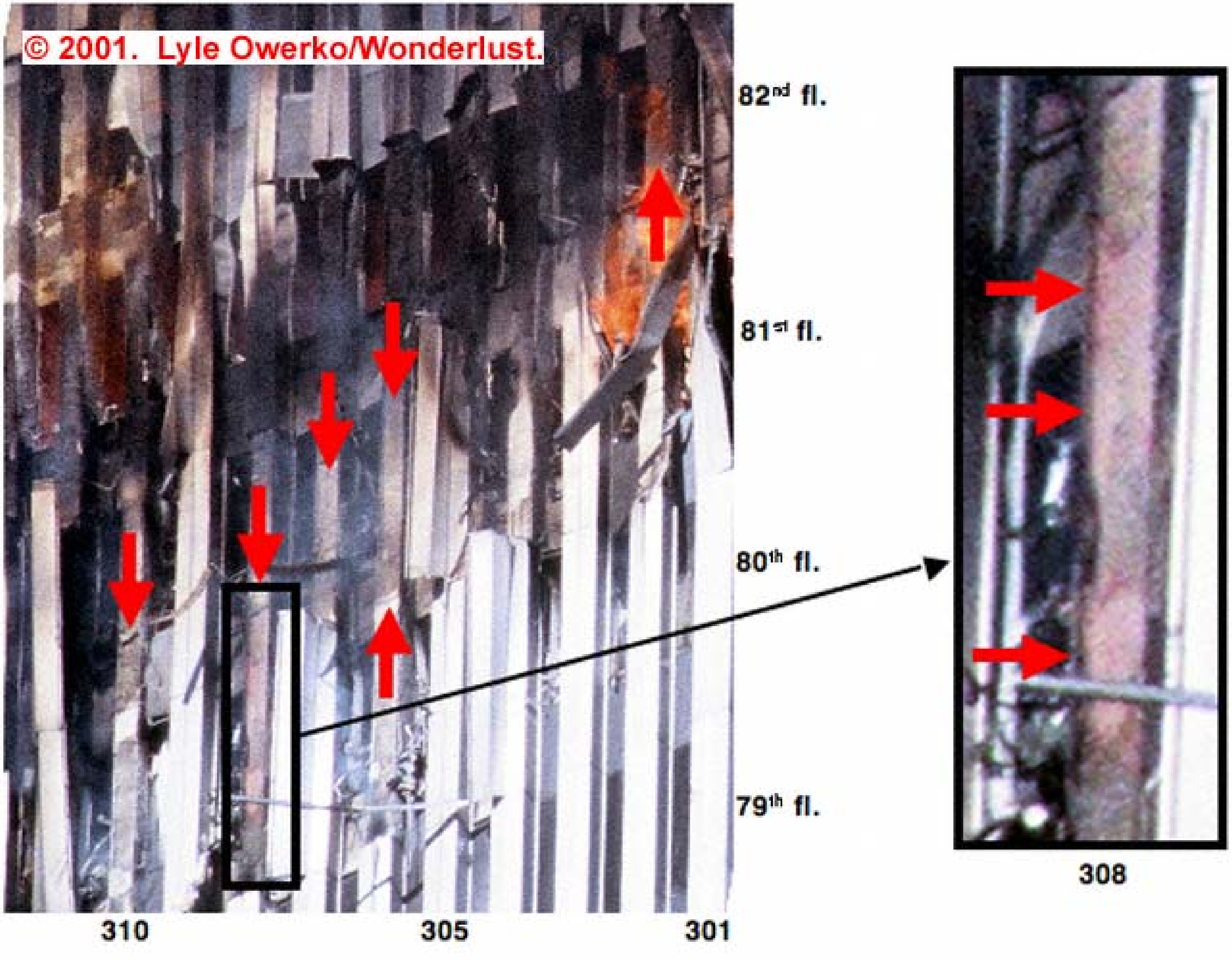
Intact (green)

Removed from outer web (white)

Covered by weatherproofing coating (blue)

Glancing Blow

East Face of WTC2



Photographic Evidence of Gross Structural Changes To Towers Prior to Collapse

Bowing of Perimeter columns: East Face of WTC2

Time: 9:21:29 AM

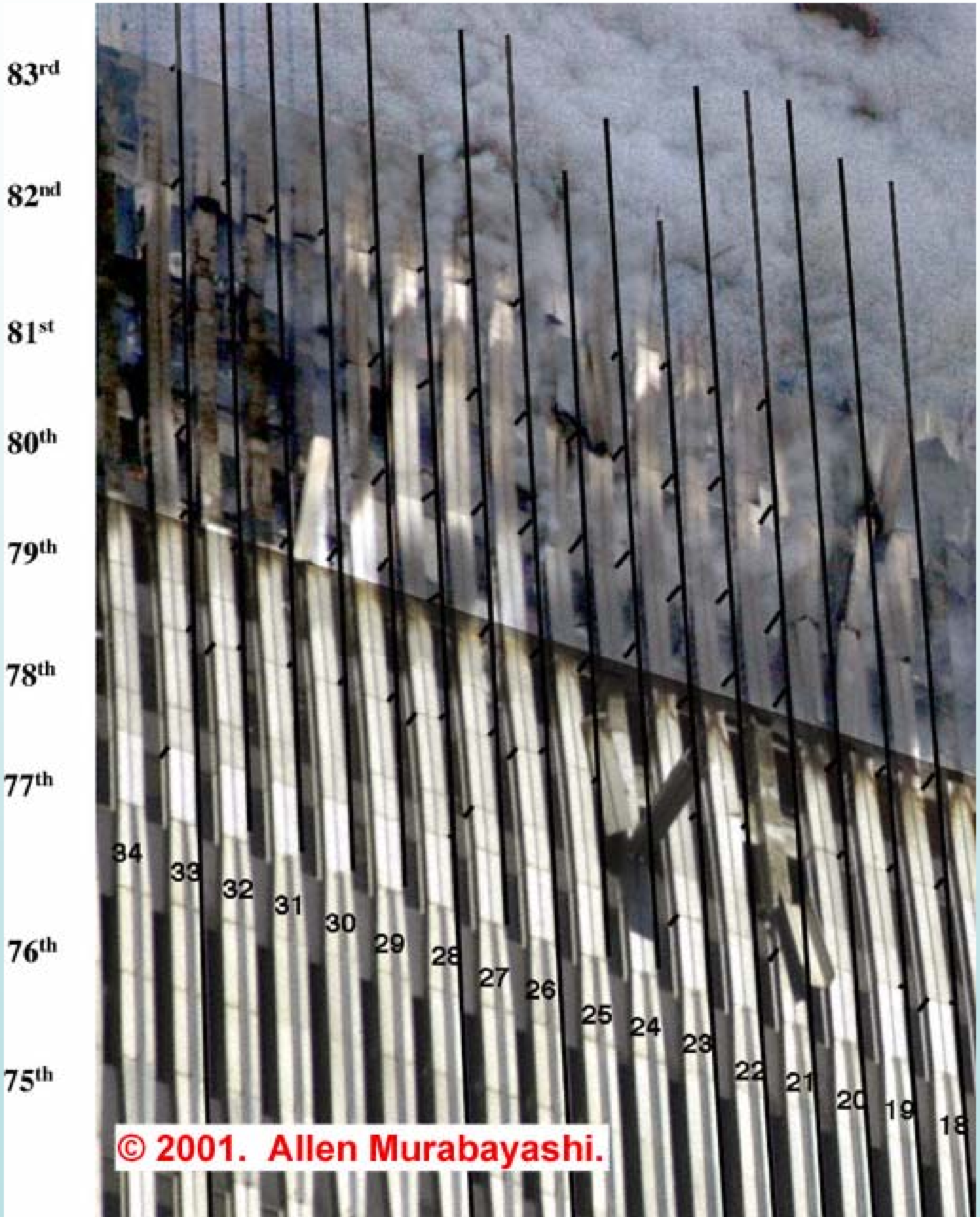
~18 minutes post impact

- **Maximum = 10 inches**

  (uncertainty ~ +/- 1 inch)

- Vertical lines establish original line of vertical columns

- Small perpendicular bars show location of inward bowing measurements



© 2001. Allen Murabayashi.

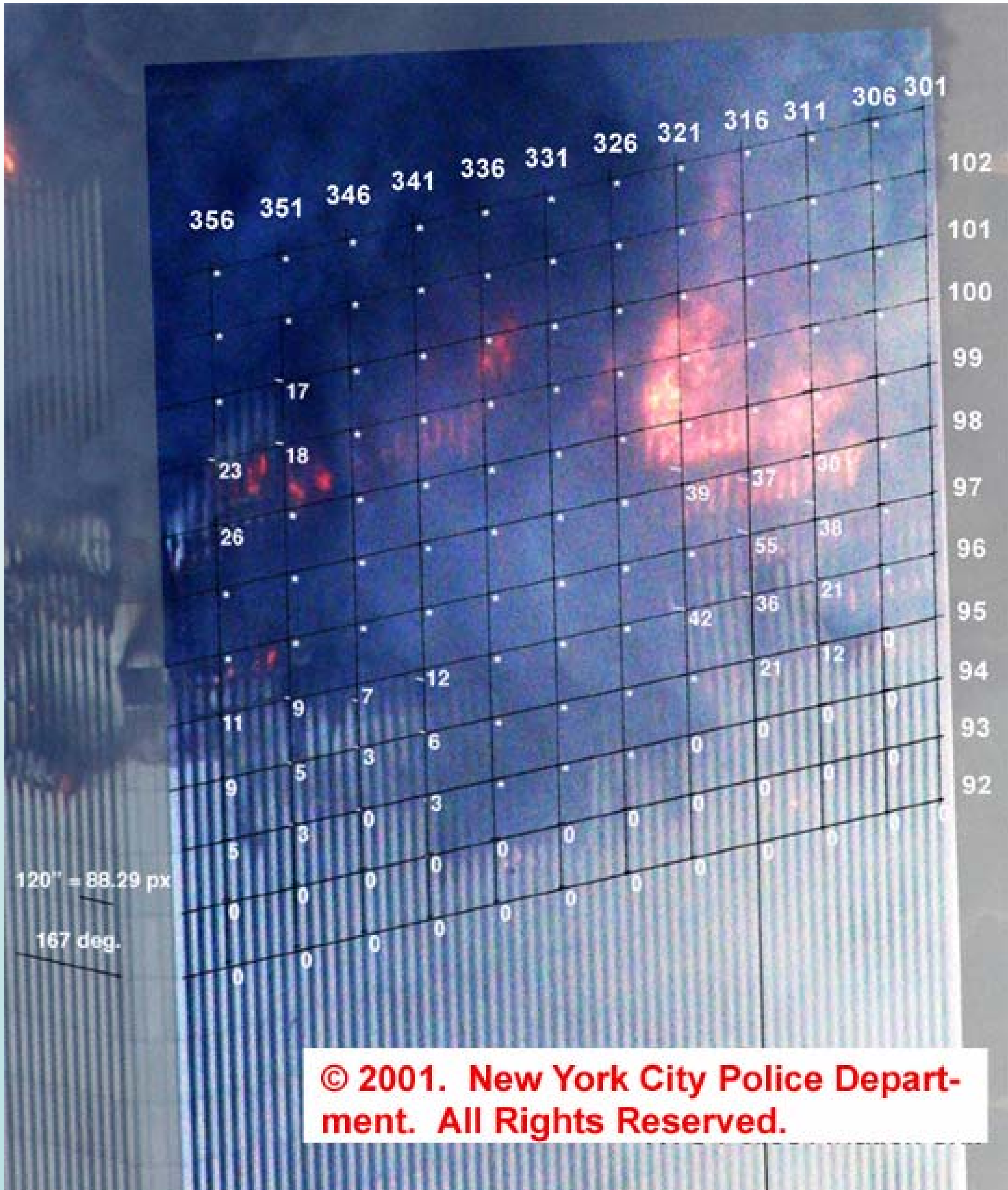
Bowing of Perimeter columns: South Face of WTC1

Time: 10:22 AM

(6 minutes before collapse)

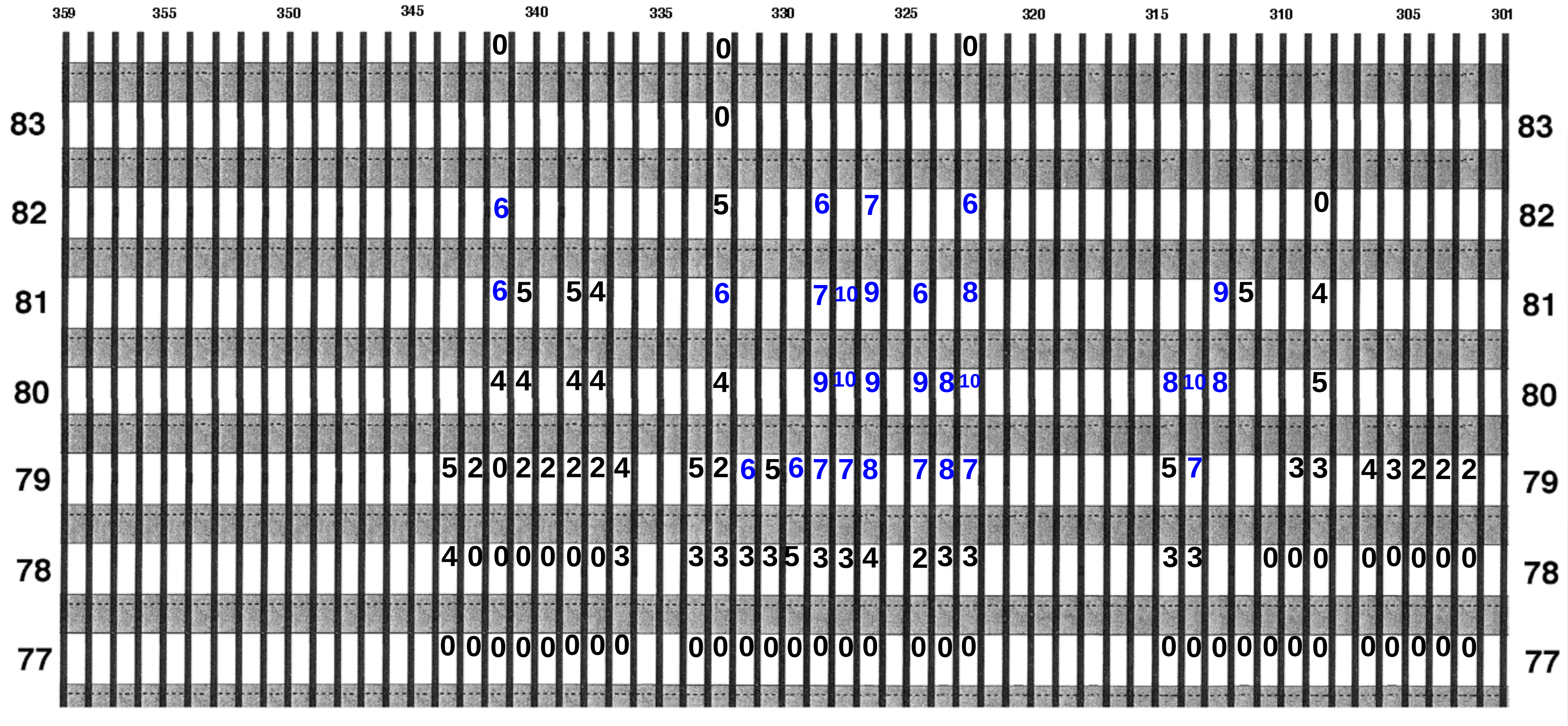
- Measurements of inward bowing (inches)

- **Maximum = 55 inches** (uncertainty ~ +/- 6 inches)
- deflection may be larger beneath smoke in center of building face
- No column deflection observed 38 minutes earlier



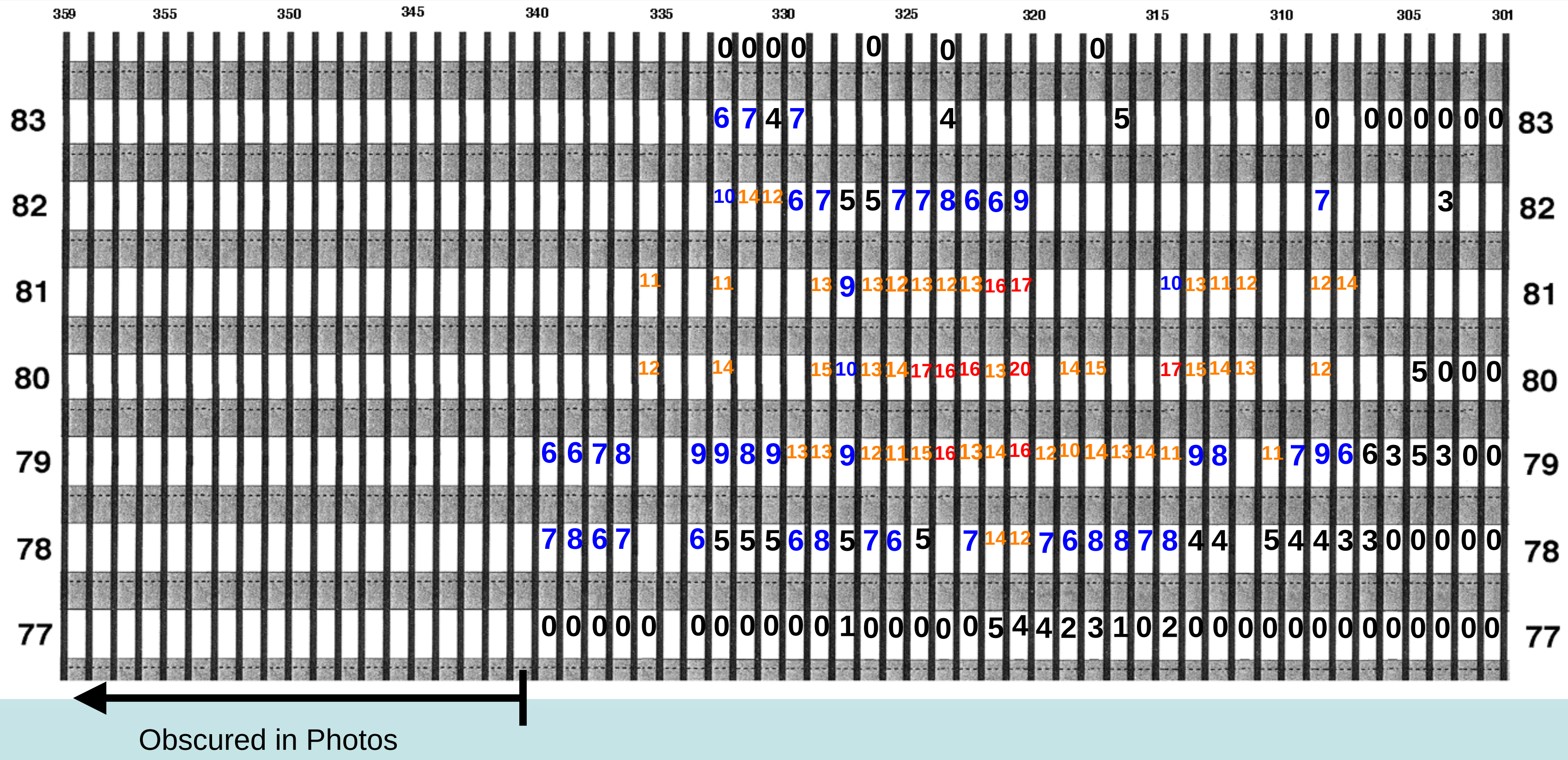
© 2001. New York City Police Department. All Rights Reserved.

East face of WTC 2
9:21:29 am, ~ 18 minutes post impact



Pull-in (inches)
Estimated uncertainty: +/- 1 inch
Empty regions have no data (smoke, damaged aluminum, etc.)

East Face of WTC 2
9:53 am., 7 minutes pre-collapse



Pull-in (inches)

Estimated uncertainty: +/- 1 inch

Empty regions have no data (smoke, damaged aluminum, etc.)

Summary of Inward Bowing Observations

- Inward column bowing observed on south face of WTC1 and east face of WTC2
- Bowing progressed over time, and, in the case of WTC1, did not exist immediately after aircraft impact
- Extent and magnitude of deflections for comparison to modeling results

Changes?

- **Identify, as specifically as possible, areas in current national building and fire model codes, standards, and practices that warrant revision**

Recommendation 11:

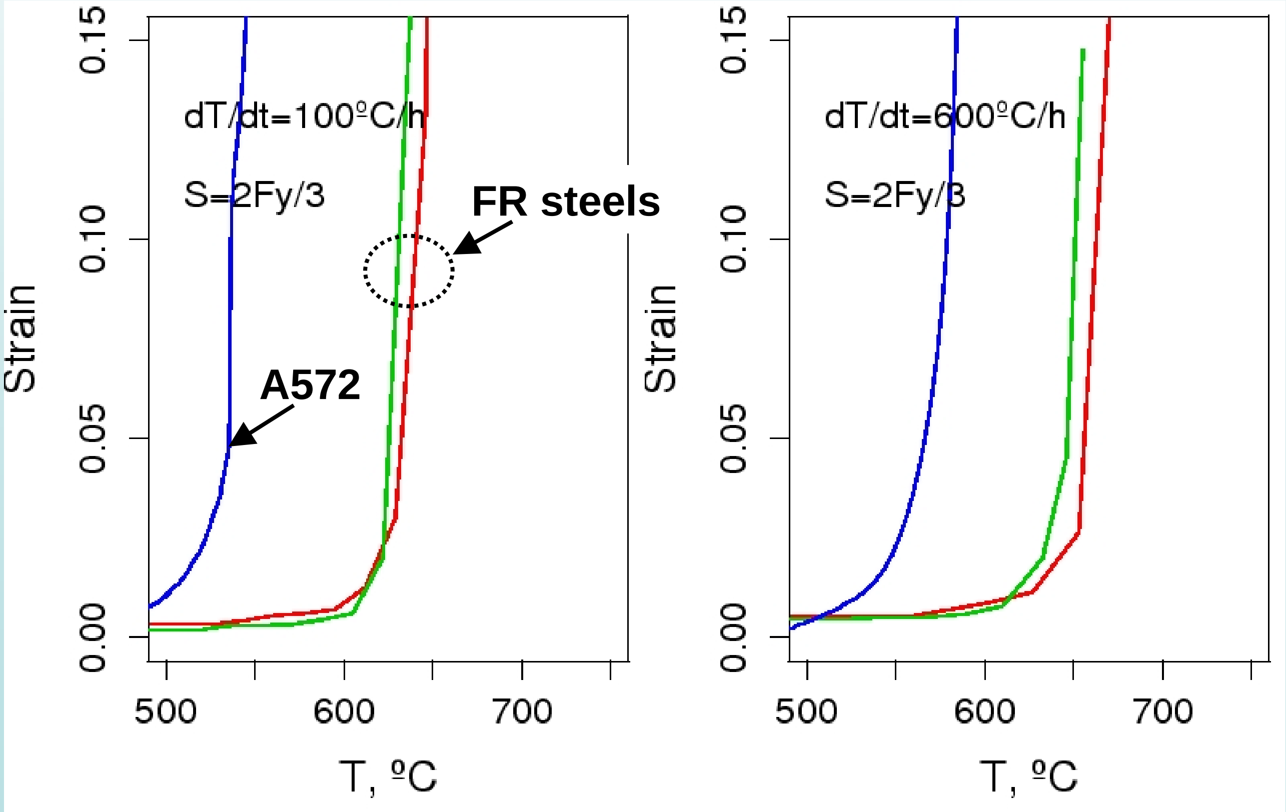
NIST recommends that the performance and suitability of advanced structural steel, reinforced and pre-stressed concrete, and other high-performance material systems should be evaluated for use under conditions expected in building fires.

Current NIST Safety of Threatened Buildings efforts:

(1) Standard test methods for evaluating fire resistive (FR) structural steel;

(2) Evaluated data on deformation of structural steel at elevated temperature.

(3) Established ASTM subcommittee to assess high temperature behavior relevant to structures.



Temperature ramp testing demonstrates potential of FR steel

Questions?