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

Project #3: Analysis of Structural Steel

Update

Frank W. Gayle
Project Leader

December 2, 2003

Materials Science and Engineering Laboratory
National Institute of Standards and Technology
U.S. Department of Commerce
frank.gayle@nist.gov

NIST

Project 3 Tasks

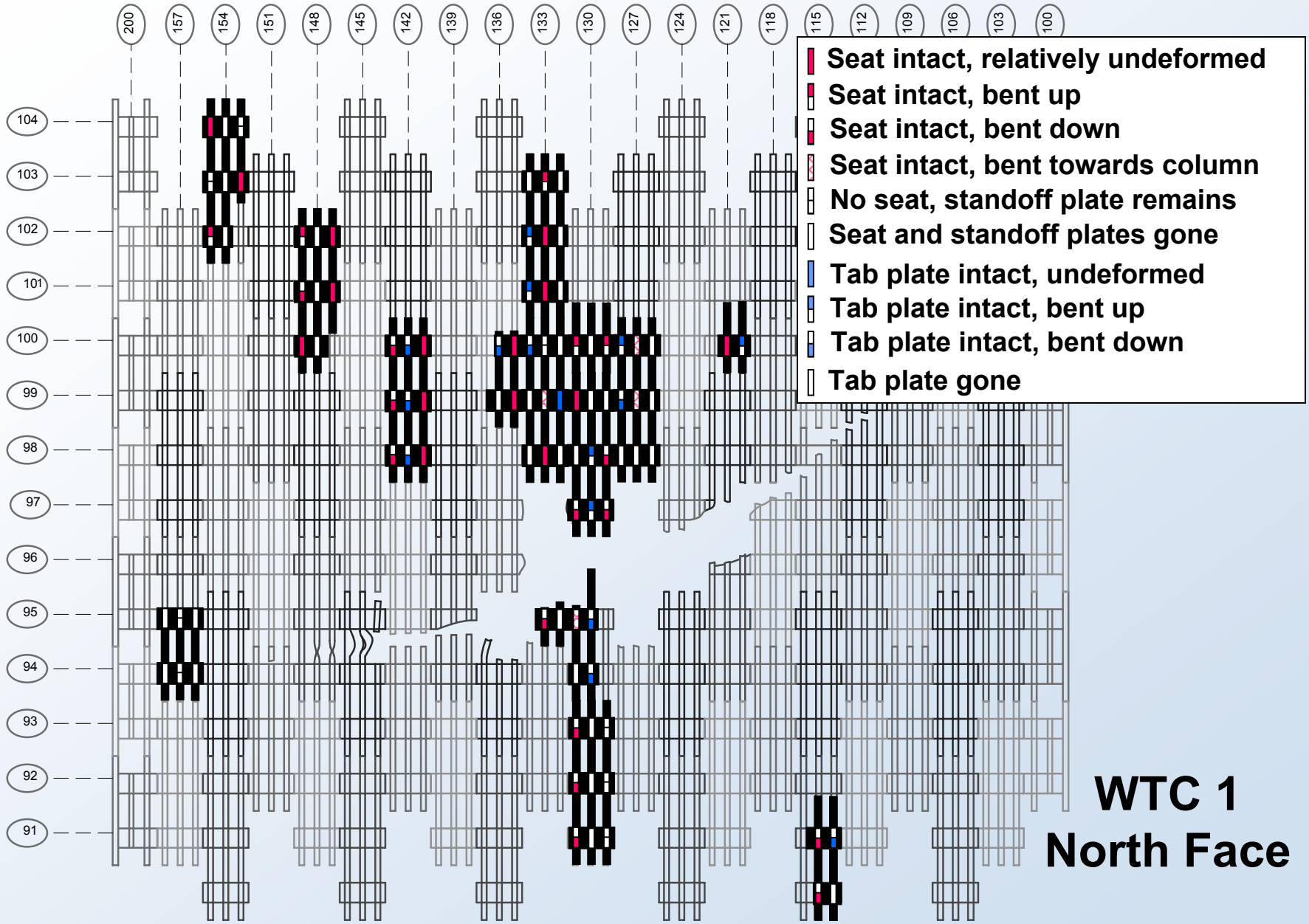
- Task 1 - Collect and catalog physical evidence
- Task 2 - Document failure mechanisms and damage
- Task 3 - Metallurgical and mechanical properties determination (room temperature, high temperature, high strain rate)
- Task 4 - Correlate specified properties with measured properties *(combined with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

- Task 1 - Collect and catalog physical evidence (99% complete)
  - Structural steel
    - *236 items catalogued, report in final review*
  - Design specifications
    - *relevant structural documents reviewed, report in final review*
  - Material specifications (ASTM, etc)
  - Supplier production information
    - *ASTM, foreign specifications reviewed*
    - *Supplier documents, other 1960's era documents used to estimate properties*
    - *report in final review*

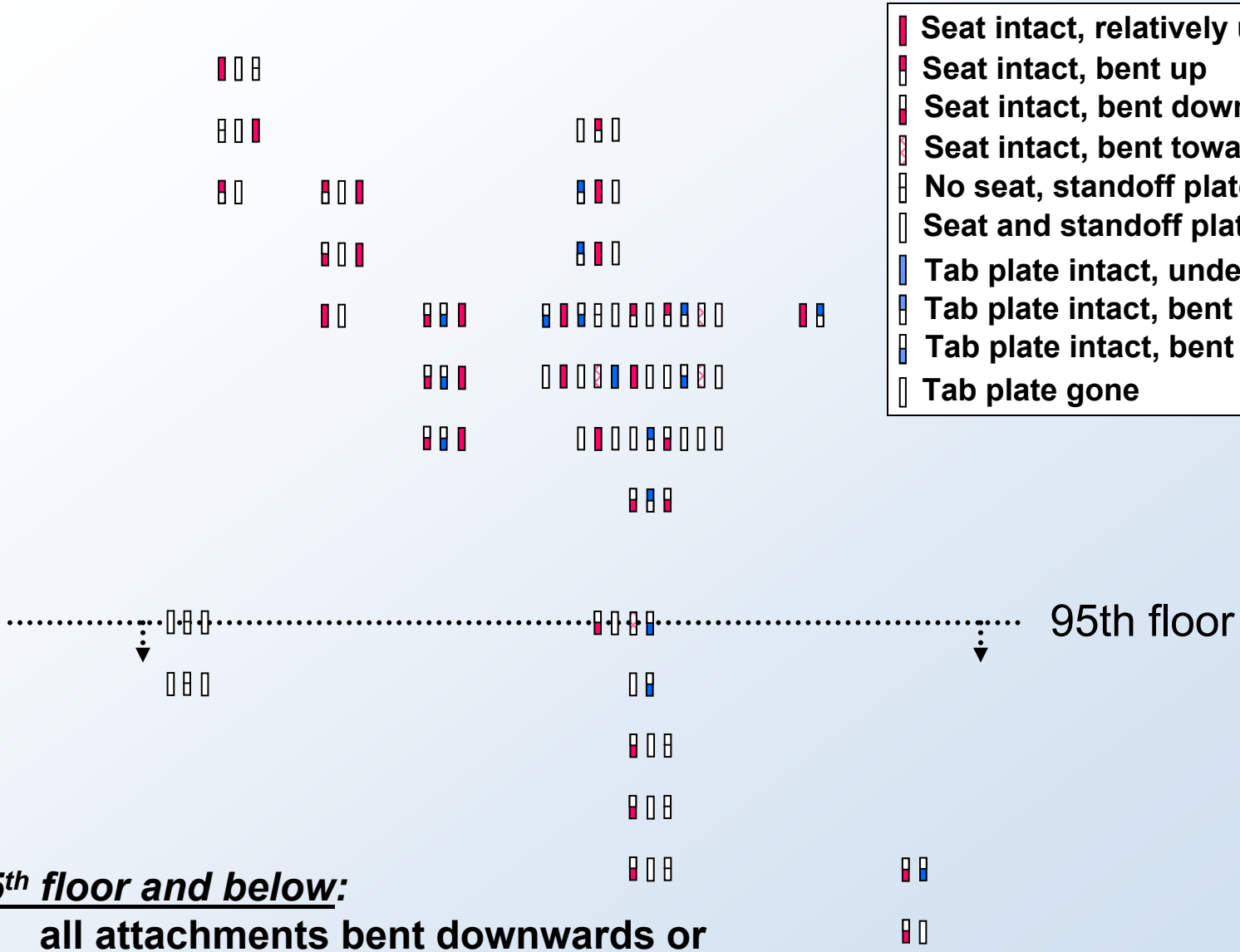
- Task 2 - Document failure mechanisms and damage (90% complete)
  - Contractor visual inspection of steel and analysis of failures completed; report drafted
  - Extensive analysis by NIST of steel
    - failure mechanisms analyzed and documented
    - repeated patterns of fracture/failure analyzed
    - failures mapped on structure
  - Photographic evidence enhanced and compared with recovered steel.

➢ January 15, 2004 anticipated completion

Floor Truss Support: Perimeter Seat Damage



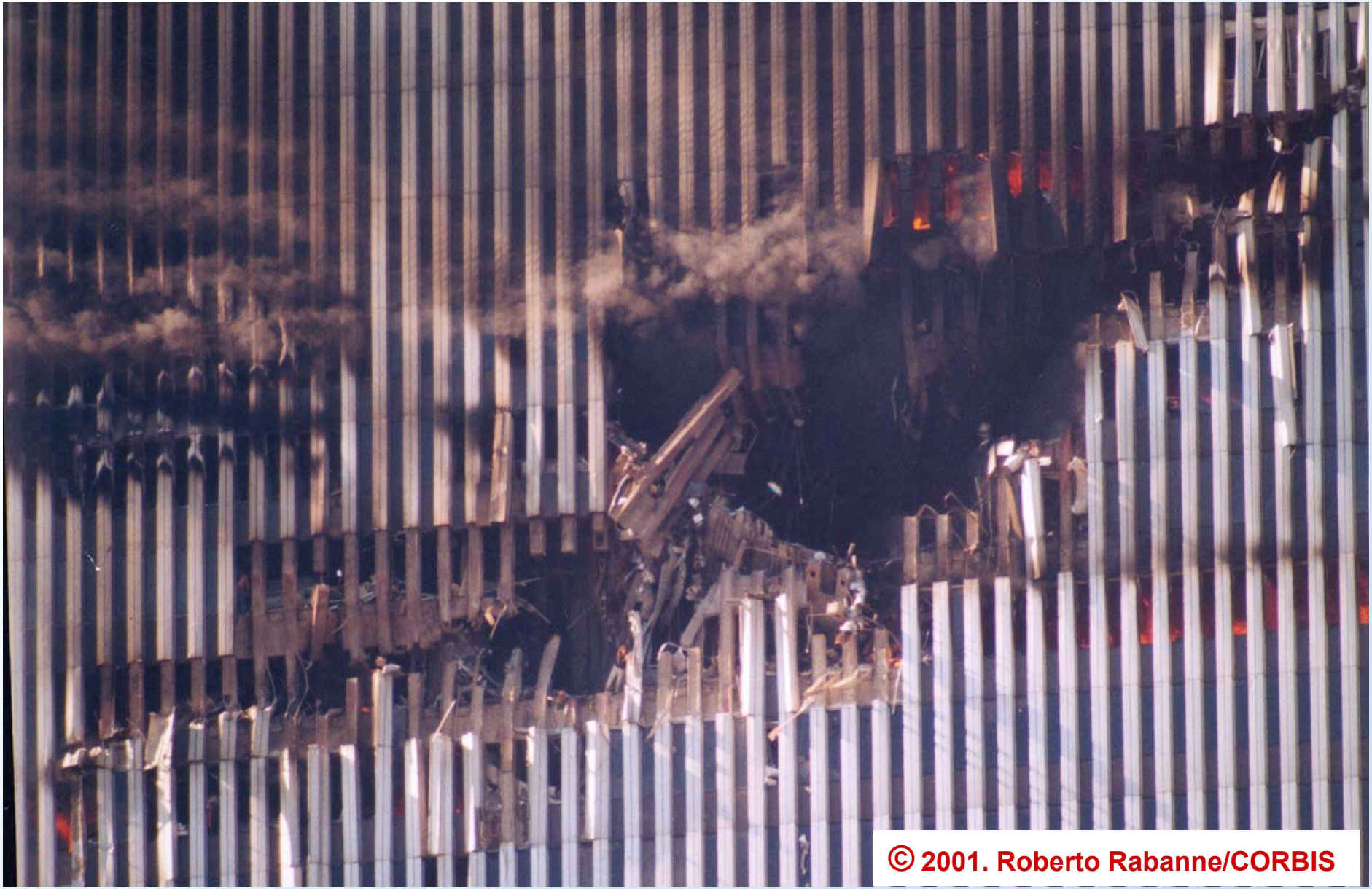
Floor Truss Support: Perimeter Seat Damage



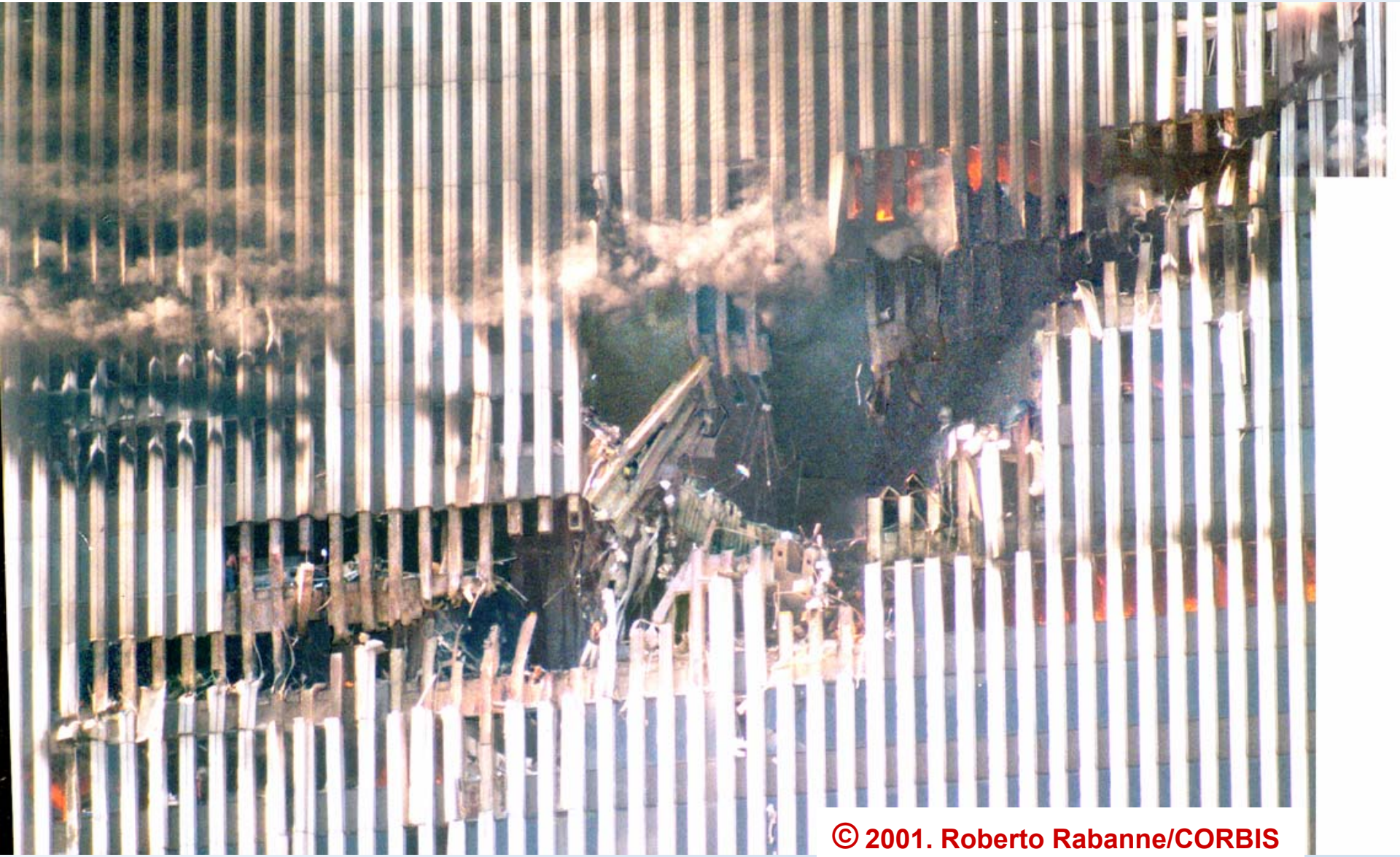
95th floor and below:

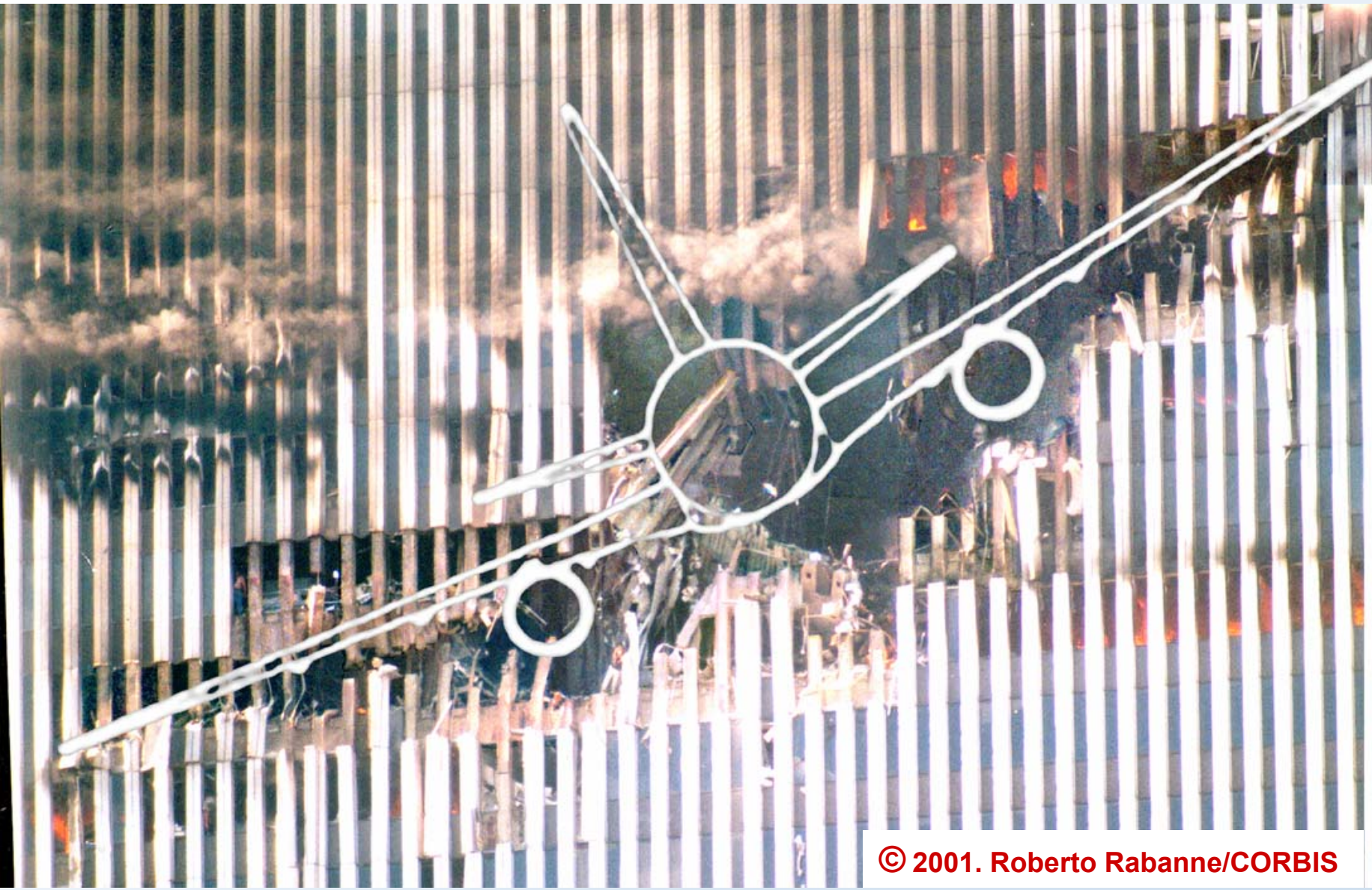
all attachments bent downwards or missing (components ripped off at welds)

Original Image

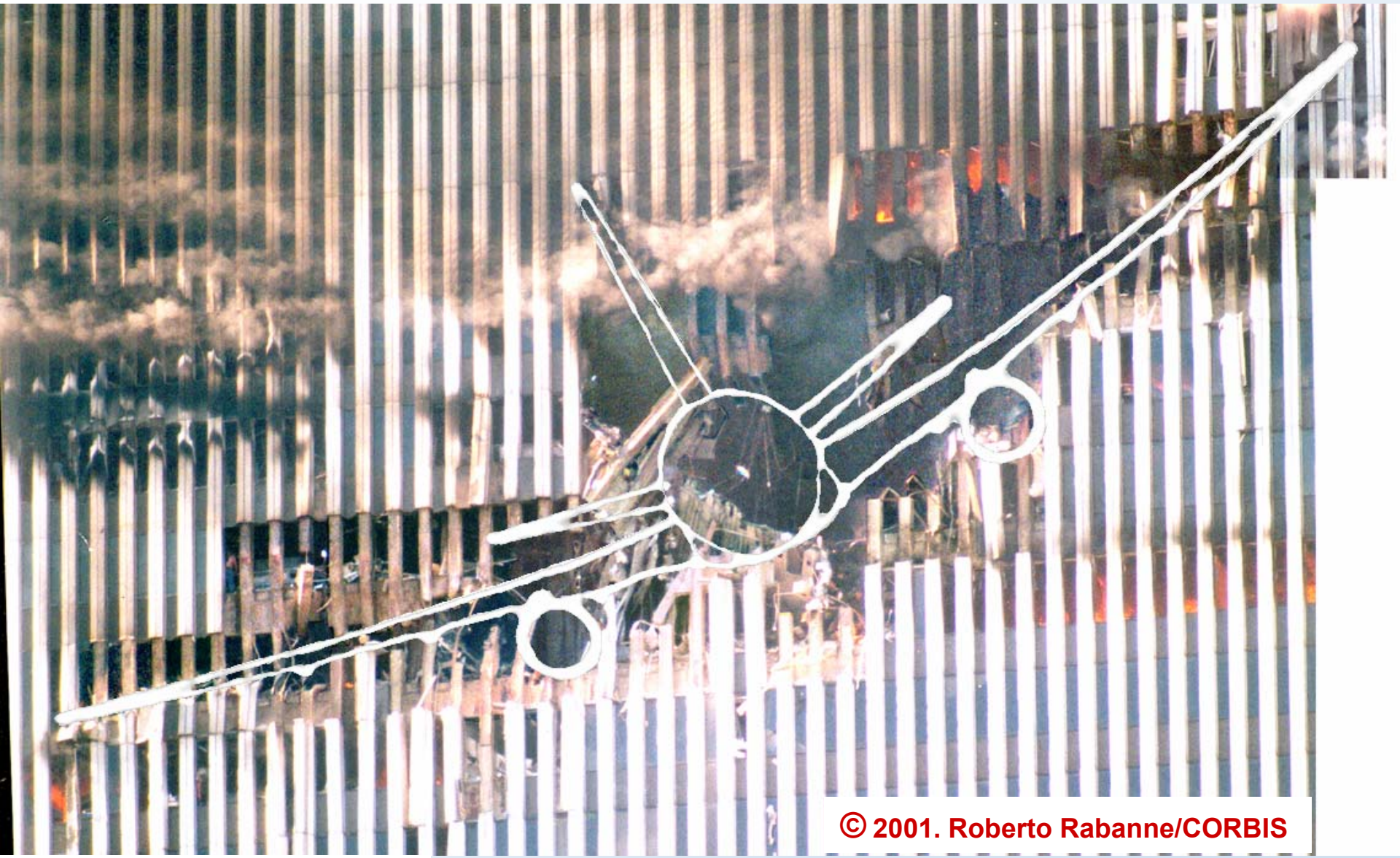


Processed Image

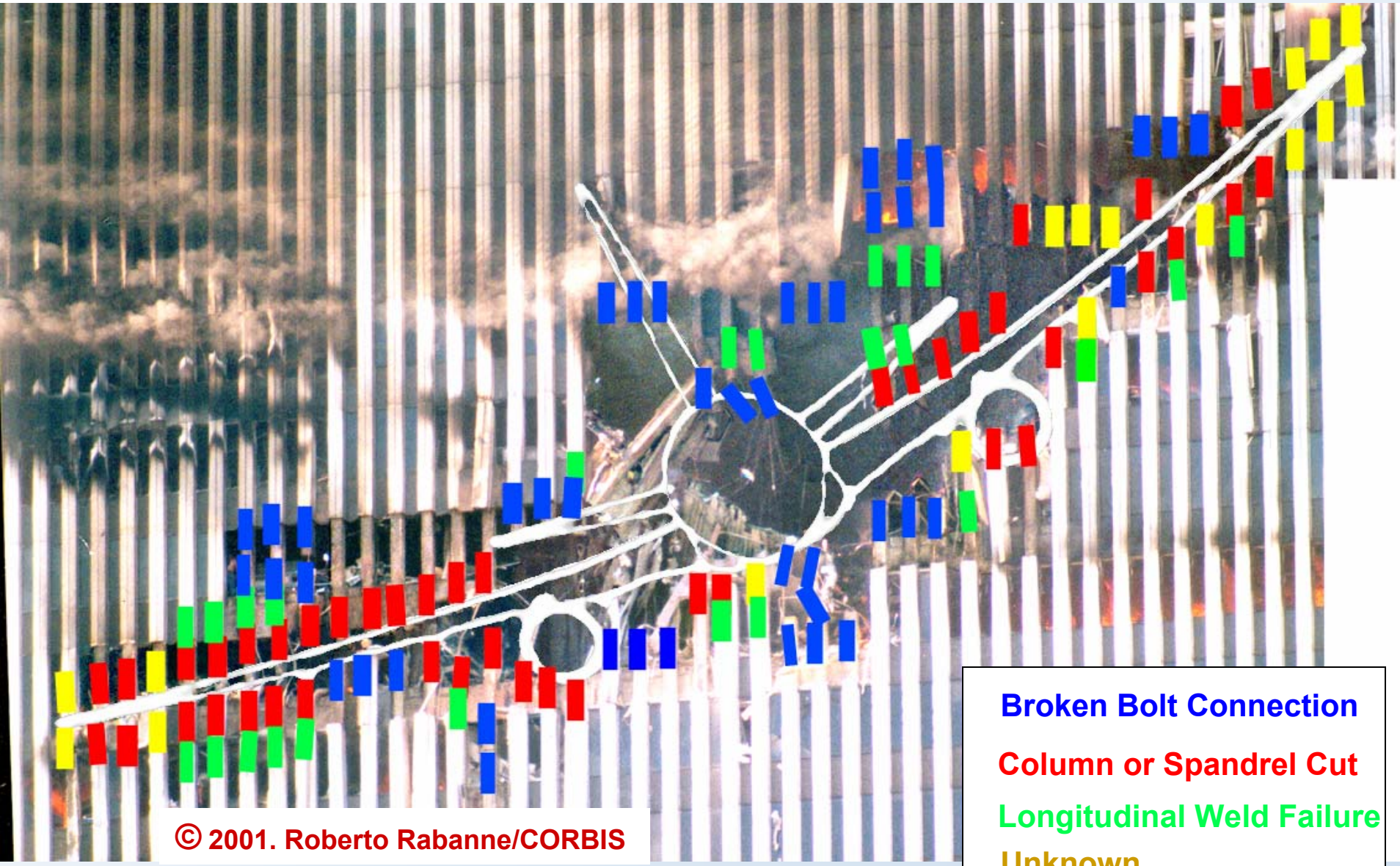




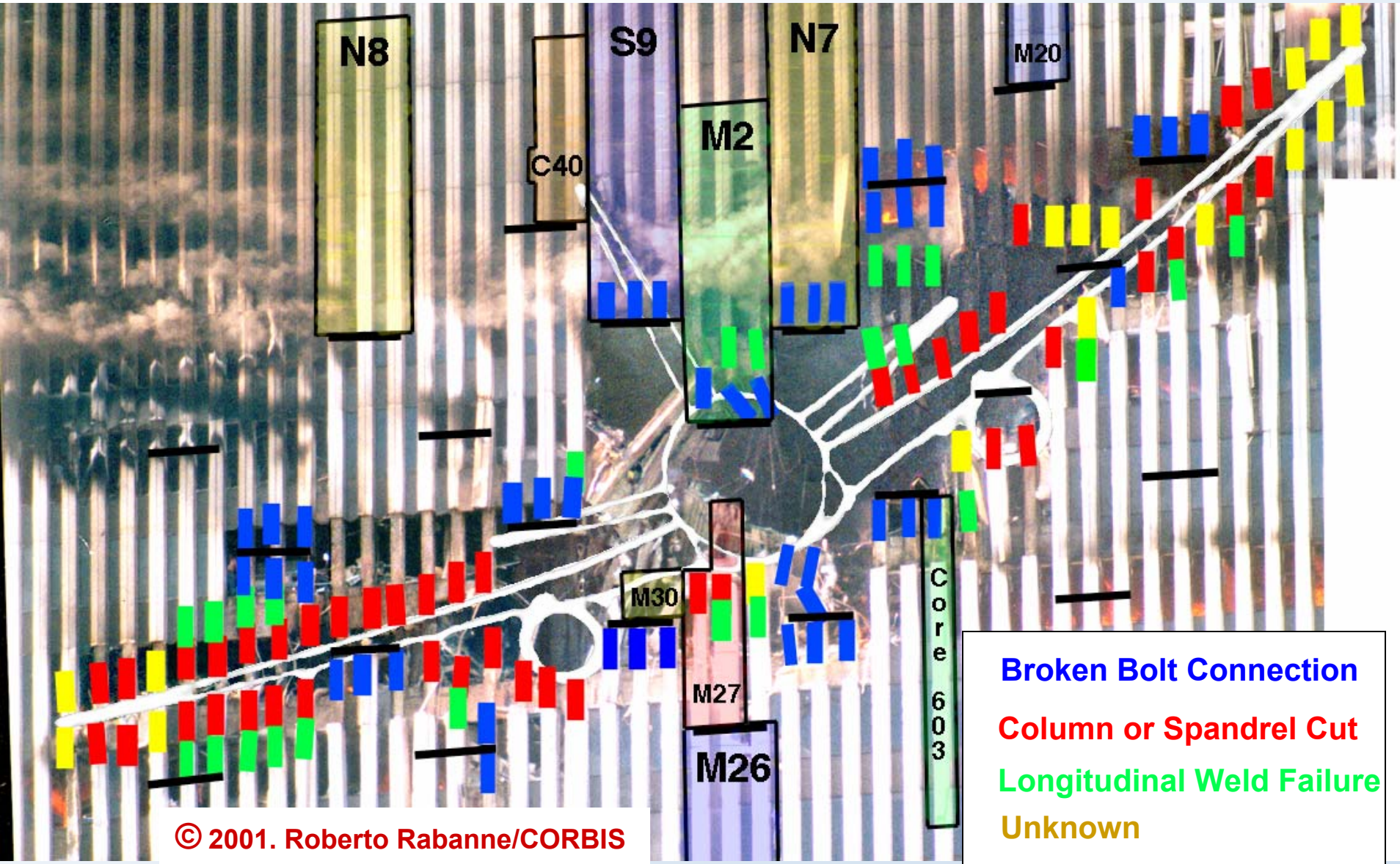
Enhancements added by NIST.



Enhancements added by NIST.

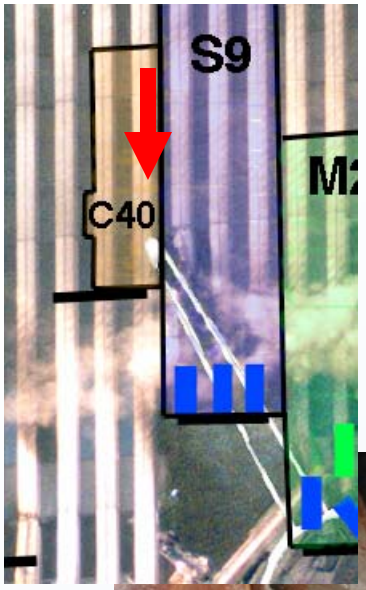


Enhancements added by NIST.



Enhancements added by NIST.

Direct comparison with state of recovered steel



C40 hit by tip of tail?

Closer examination shows collision damage unlikely – damage occurred during fall

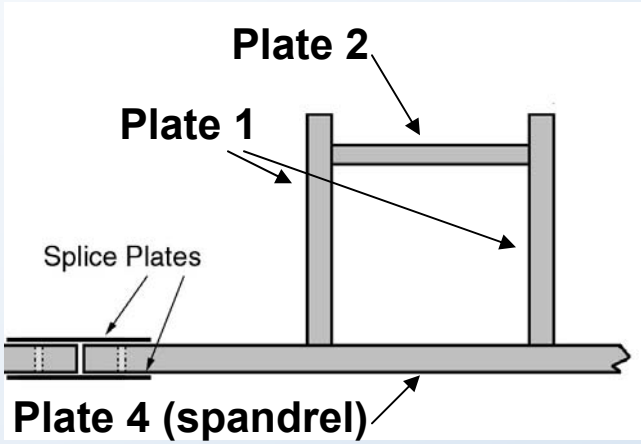
Enhancements added by NIST.

Tasks

- Task 3 - Metallurgical and mechanical properties determination (room temperature, high temperature, high strain rate)
- Tensile properties determined for all perimeter columns
  - *test values compared with estimated properties (Task 1)*
  - *ideal stress strain curves developed*
  - *material parameters supplied for models*
- High Strain Rate properties determined for 6 relevant perimeter columns
- Truss rod and angles characterized
- Creep testing on hold:
  - Possibly not necessary for WTC 1 and 2
  - Review needs with contractor modeling fire response
  - *Allows earlier completion of high temp tensile properties*

Model Stress-Strain Curves

Perimeter column plates 1, 2, 4 – *Preliminary test data*

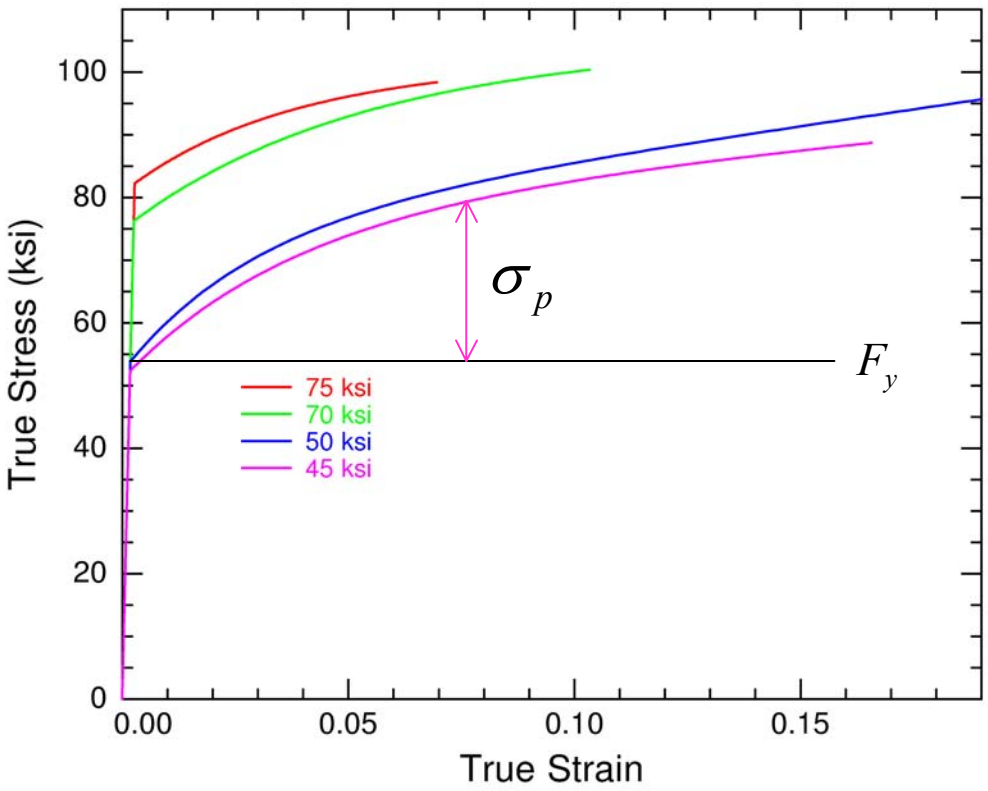


Grade	Best estimate literature	NIST measured mean value	Steel source
FY ksi	***FY*** ksi	***FY*** ksi	
36	40	39	
42	57	56	Yawata "A 441 modified"
45	57	56	Yawata "A 441 modified"
50	58	58	Yawata "A 441 modified"
55	62	64	Yawata "A 441 modified"
60	67	66	Yawata "A 441 modified"
65	73	73	Yawata WEL-TEN 60R
70	78	77	Yawata WEL-TEN 62
75	84	83	Yawata WEL-TEN 62
80	90	95	Yawata WEL-TEN 70
85	105	108	Yawata "A 514 mod" (WEL-TEN 80C)
90	105	108	Yawata "A 514 mod" (WEL-TEN 80C)
100	105	108	Yawata "A 514 mod" (WEL-TEN 80C)

Mill reports used where available to estimate F_y, otherwise 1960s era literature studies on structural steel.

NIST

Model Stress-Strain Curves



Generation of model curves

- Use standard *E* (stiffness) up to yield strength
- Compute work-hardening from average of NIST-measured curves
- Model plastic behavior with Voce's law
- Correct for dynamic effects

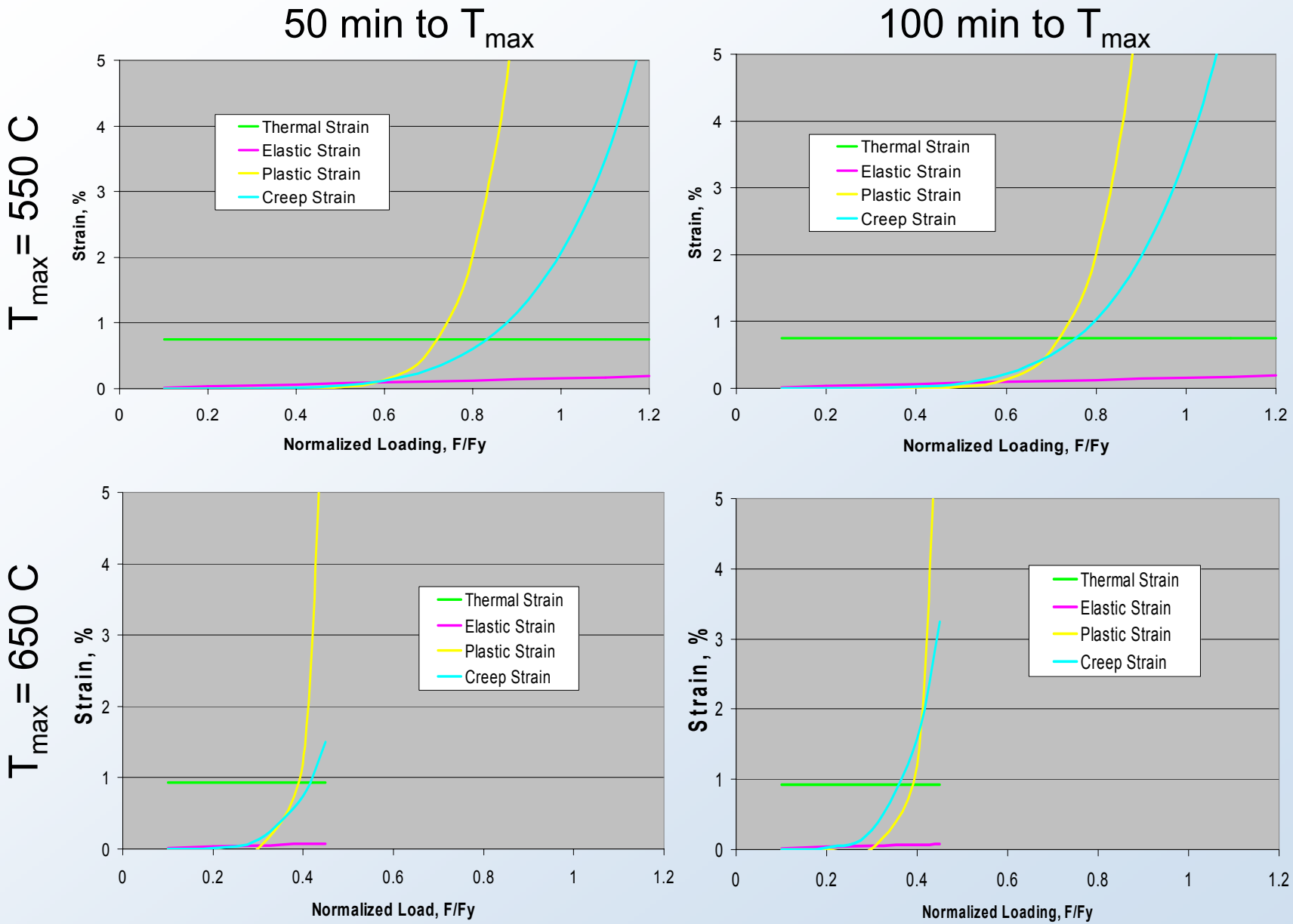
Voce's nonlinear isotropic hardening:

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

NIST

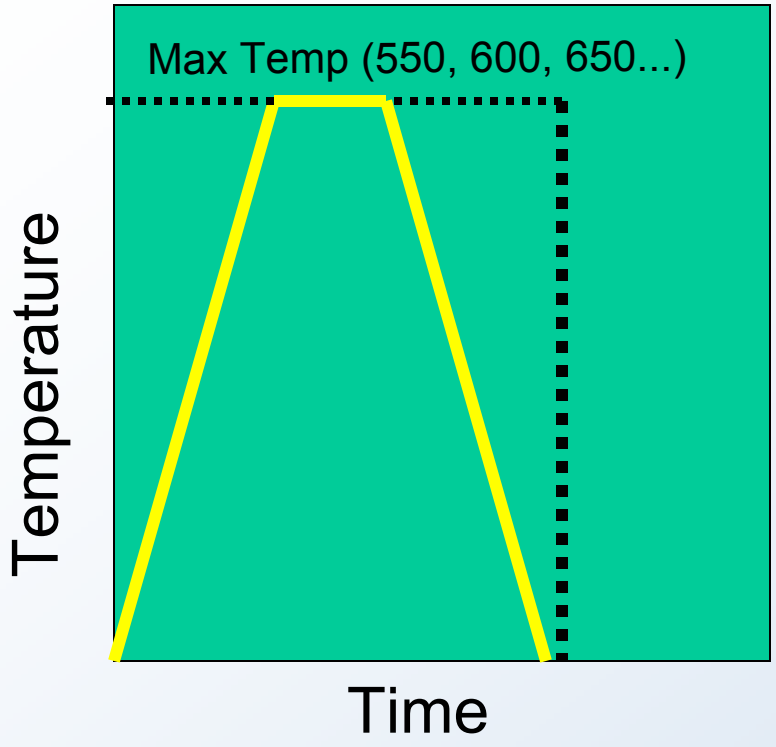
Creep, Plastic, and Thermal Strain – Relative Magnitude

$$\varepsilon_{TOTAL} = \varepsilon_{thermal} + \varepsilon_{elastic} + \varepsilon_{plastic} + \varepsilon_{creep}$$

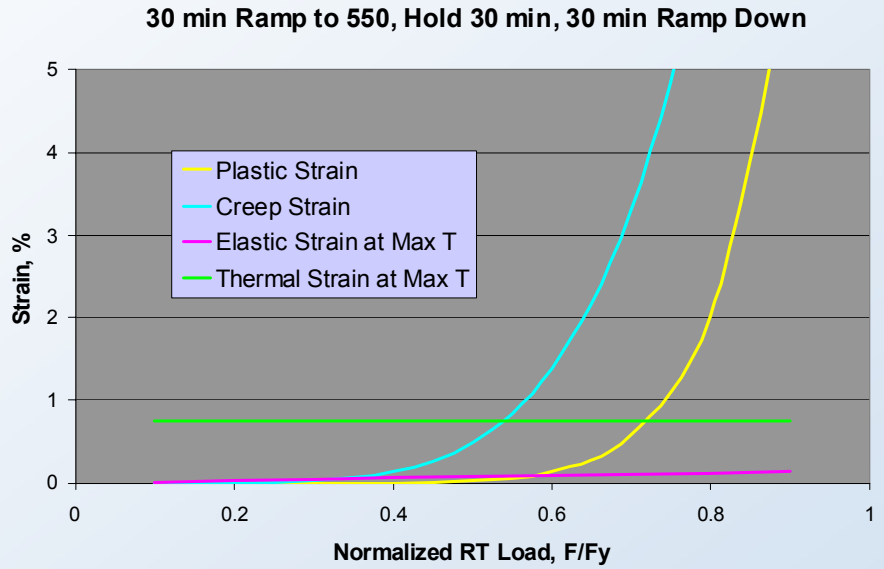


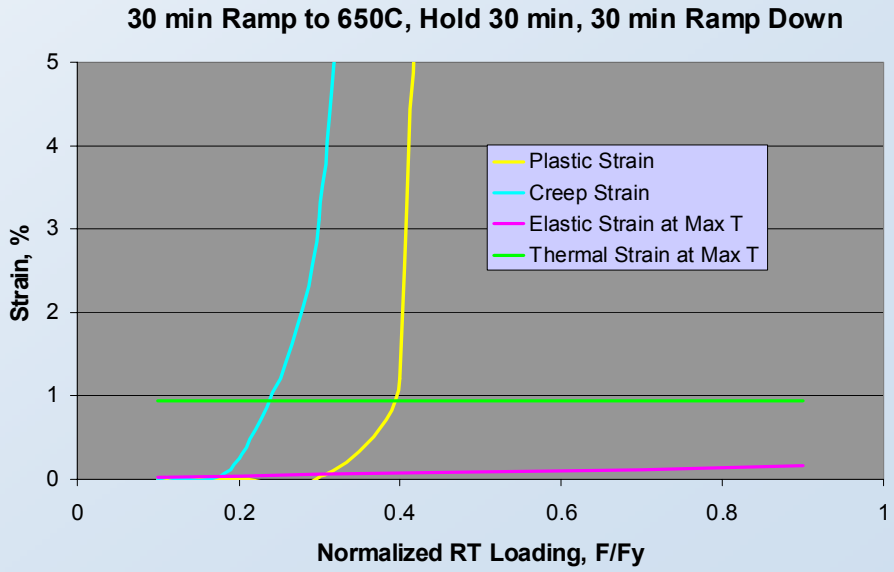
Creep, Plastic, and Thermal Strain – Relative Magnitude

$$\varepsilon_{TOTAL} = \varepsilon_{thermal} + \varepsilon_{elastic} + \varepsilon_{plastic} + \varepsilon_{creep}$$



For even short hold times at high temperature, *creep strain may dominate total strain*.





Current Status of Mechanical Test Program

	% complete
RT tensile tests (quasistatic)	95%
High temperature tensile tests	40%
Creep (TBD)	--
High Strain Rate (tensile)	65%
High Strain Rate (compression)	45%
Impact (Charpy)	90%
Welds	30%
Bolts (tensile & High Strain Rate)	50%

- Task 5 - Characterize thermal excursions of steel
  - Paint condition used to map upper limits to temperature exposure
  - ➢ *Analysis completion target date January 2004*
- Task 6 - Final report

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