# 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**


NIST

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

***Recovered WTC steel will be characterized to:***

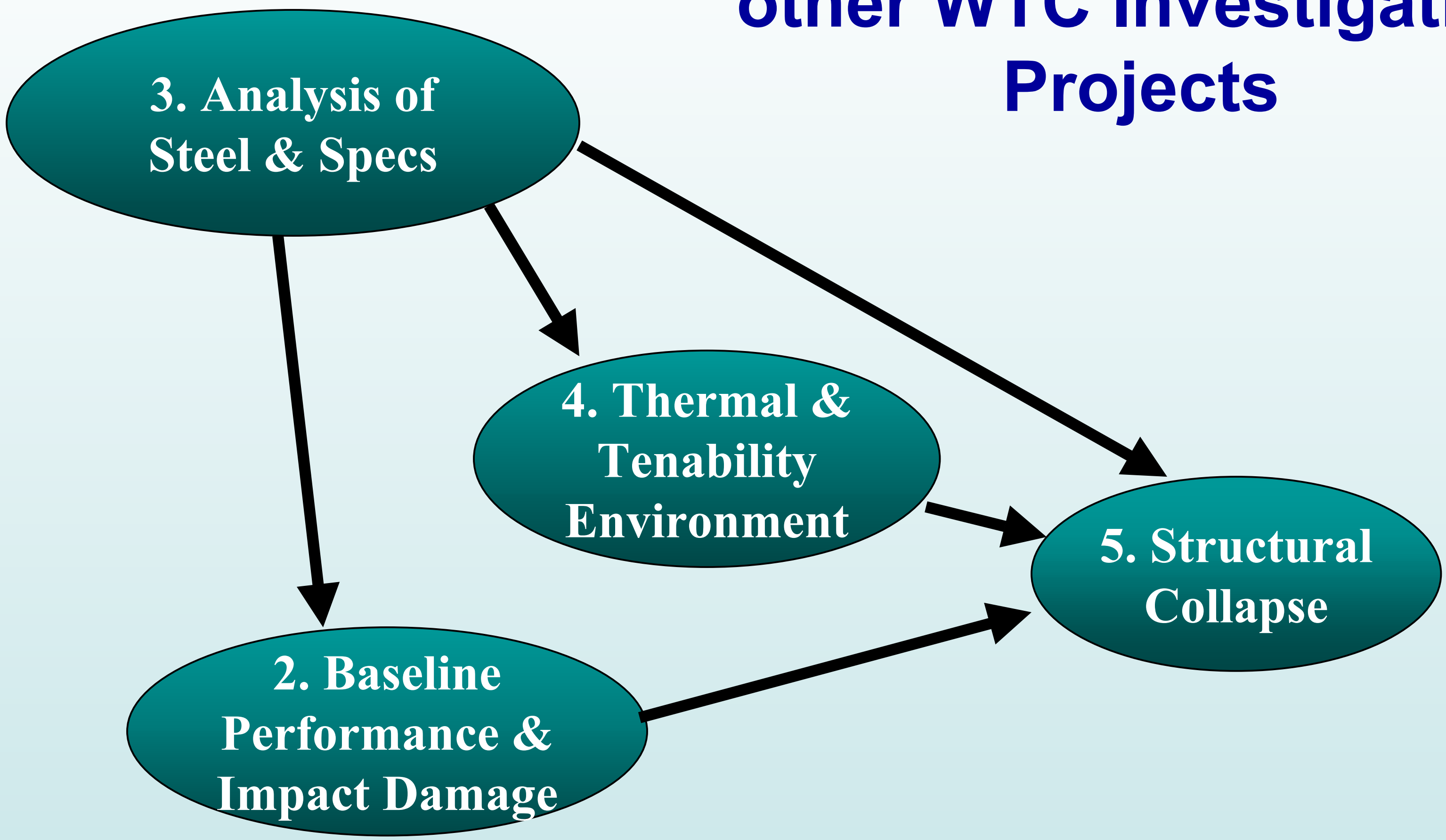
Compare tested properties to specified yield strengths (and by location)

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

# Project 3 interaction with other WTC Investigation Projects




**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

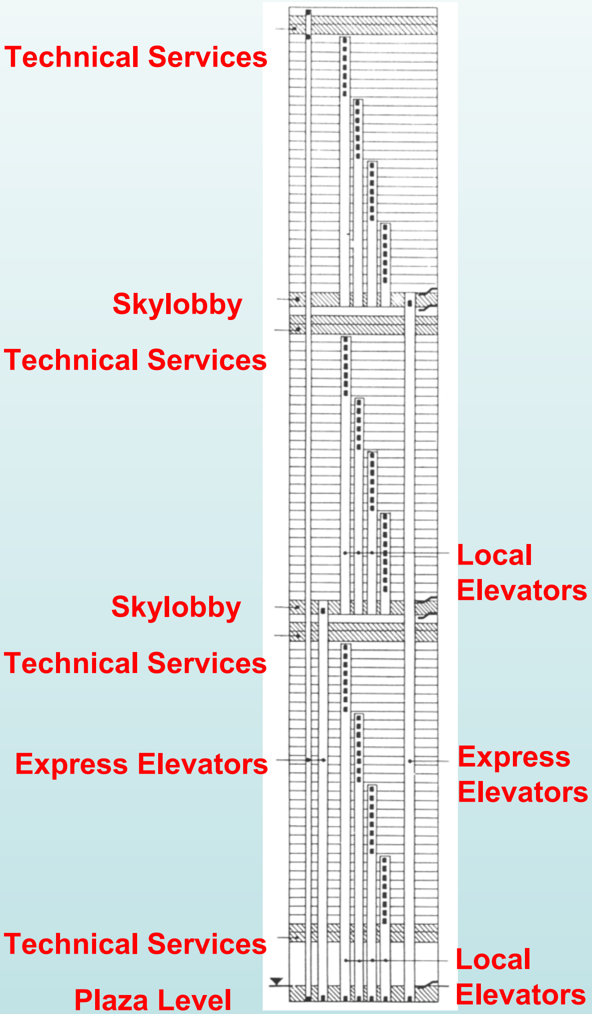
## Task 1 - Collect and catalog physical evidence

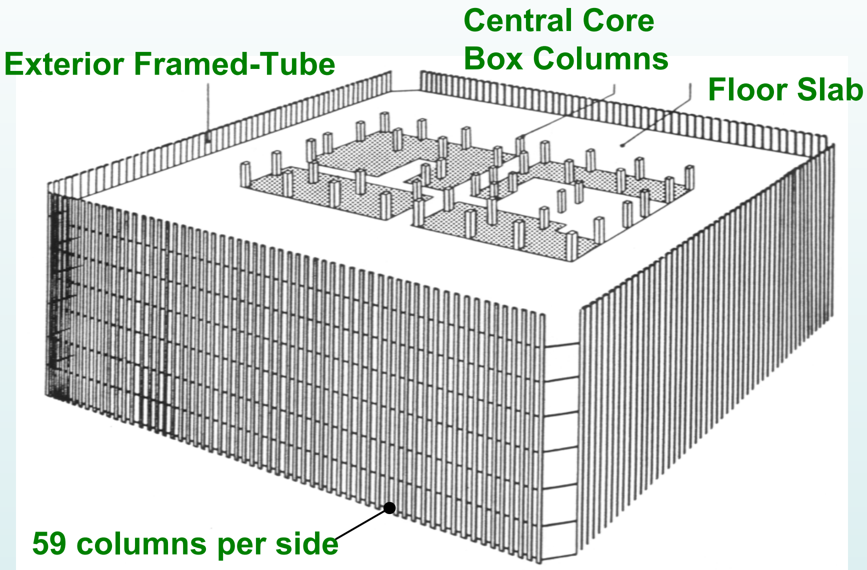
- Structural steel
- Design specifications
  - sections & minimum yield strengths
  - documents from:
    - Port Authority of New York and New Jersey
    - Leslie E. Robertson Associates
- Material specifications (ASTM, etc)
- Supplier production information

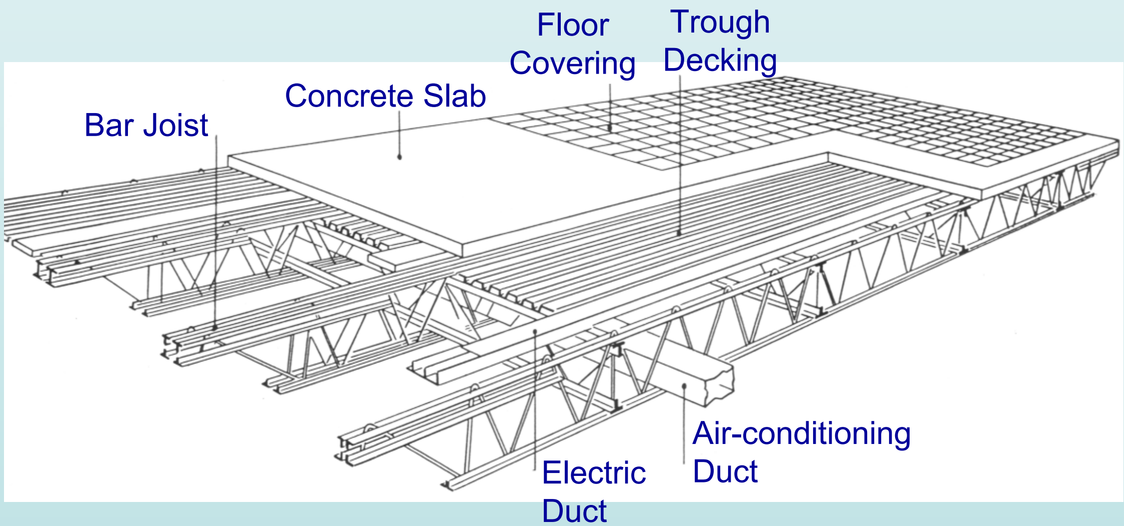
  Yawata Steel (now Nippon Steel)
  Laclede Steel
  Many others

# WTC Tower Design

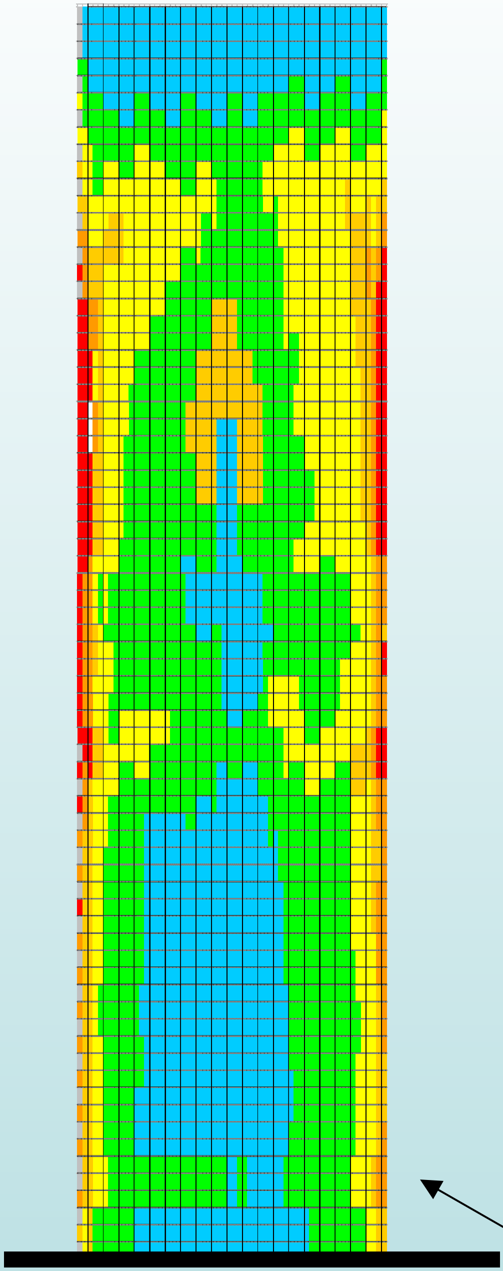
110 stories



WTC 1, North Face



Simulated distribution of perimeter column yield strengths

**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

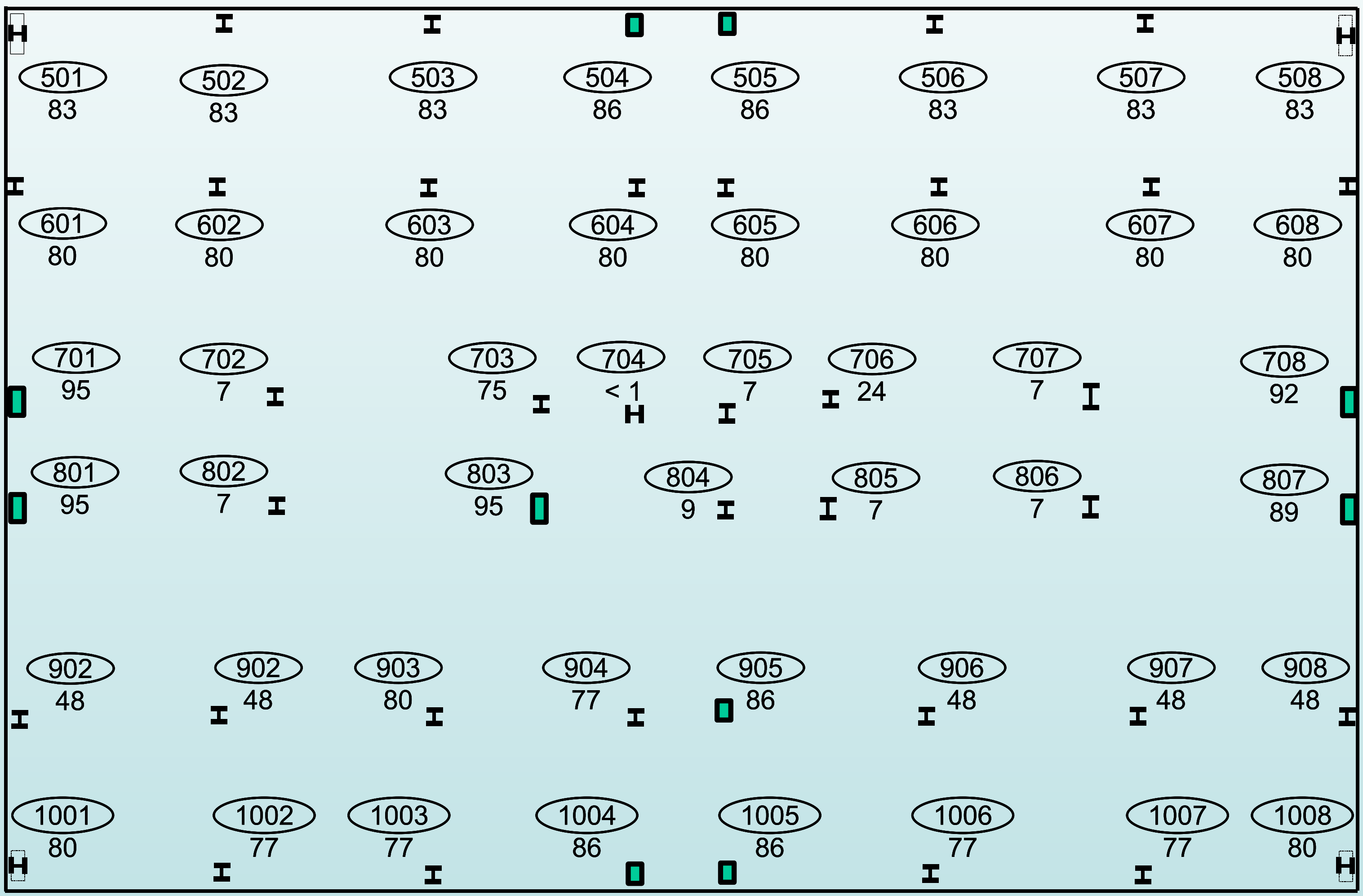
***Wind loads*** **primary factor in perimeter column design.**

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

# Core Columns

## Transition floors from welded box column to wide flange columns

### Columns and orientations shown for 84th floor



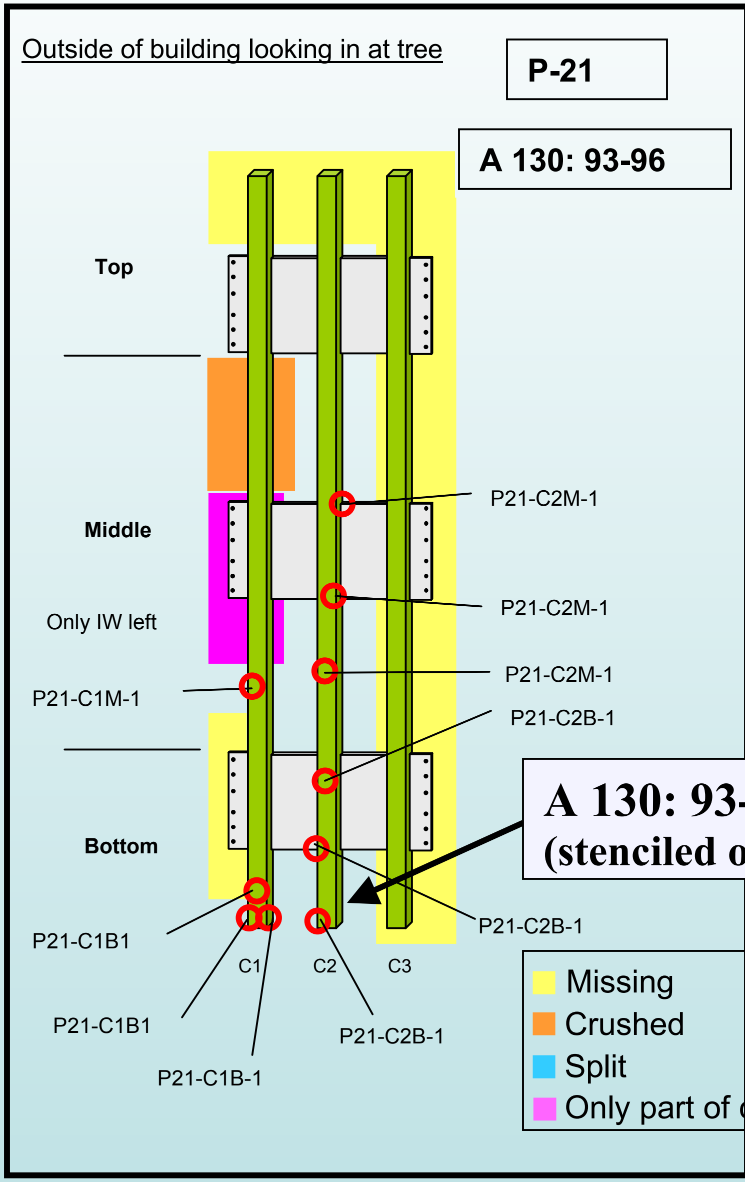
# Steel Search, Collection, Logging and Shipping to NIST


**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**

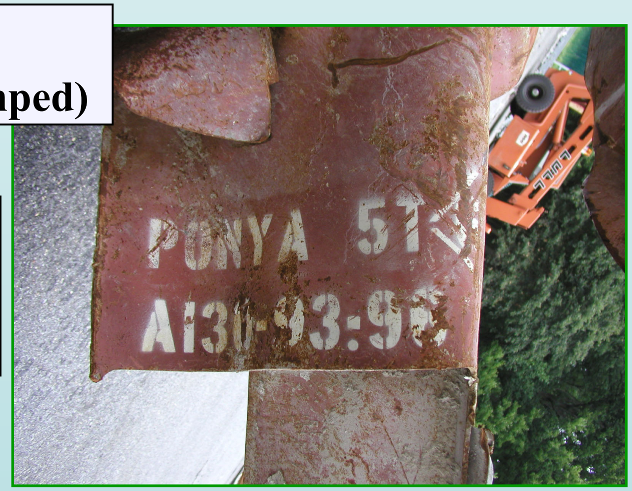
# Salvaged Steel at NIST

# DOCUMENTATION OF SAMPLE REMOVAL




A 130: 93-96
(stenciled or stamped)

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

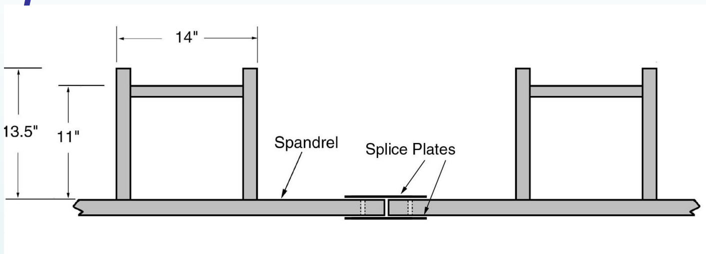




**Documentation extremely important!**

Catalog of Steel – *according to class*

| | |
|---|---|
| **236** | **TOTAL PIECES** |
| | |
| 93 | Perimeter panel sections |
| 11 | Box beams / Core Columns |
| 43 | Wide Flange sections (WF) |
| 23 | Trusses |
| 25 | Channels |
| 2 | "Bowtie" pieces of exterior wall |
| 7 | Coupons from Bldg 5 |
| 32 | Miscellaneous (bolts, other) |

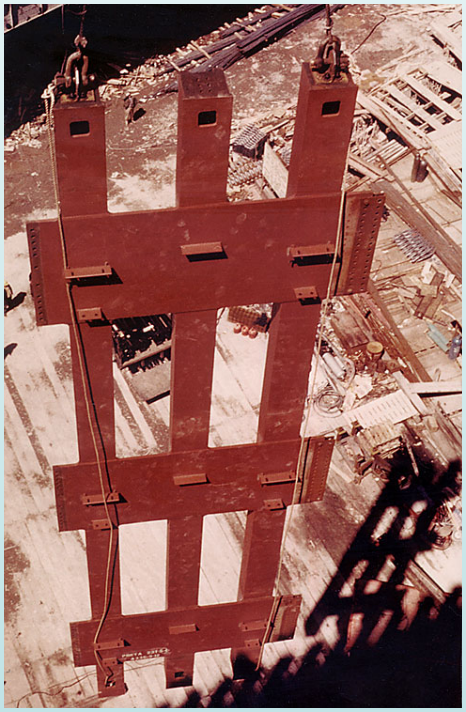
# Catalog of Steel – *identified perimeter panels*




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*



**<u>WTC 1</u>**
- 25 panels
- 21 near impact floors
  - 3 hit directly by plane

**<u>WTC 2</u>**
- 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.*

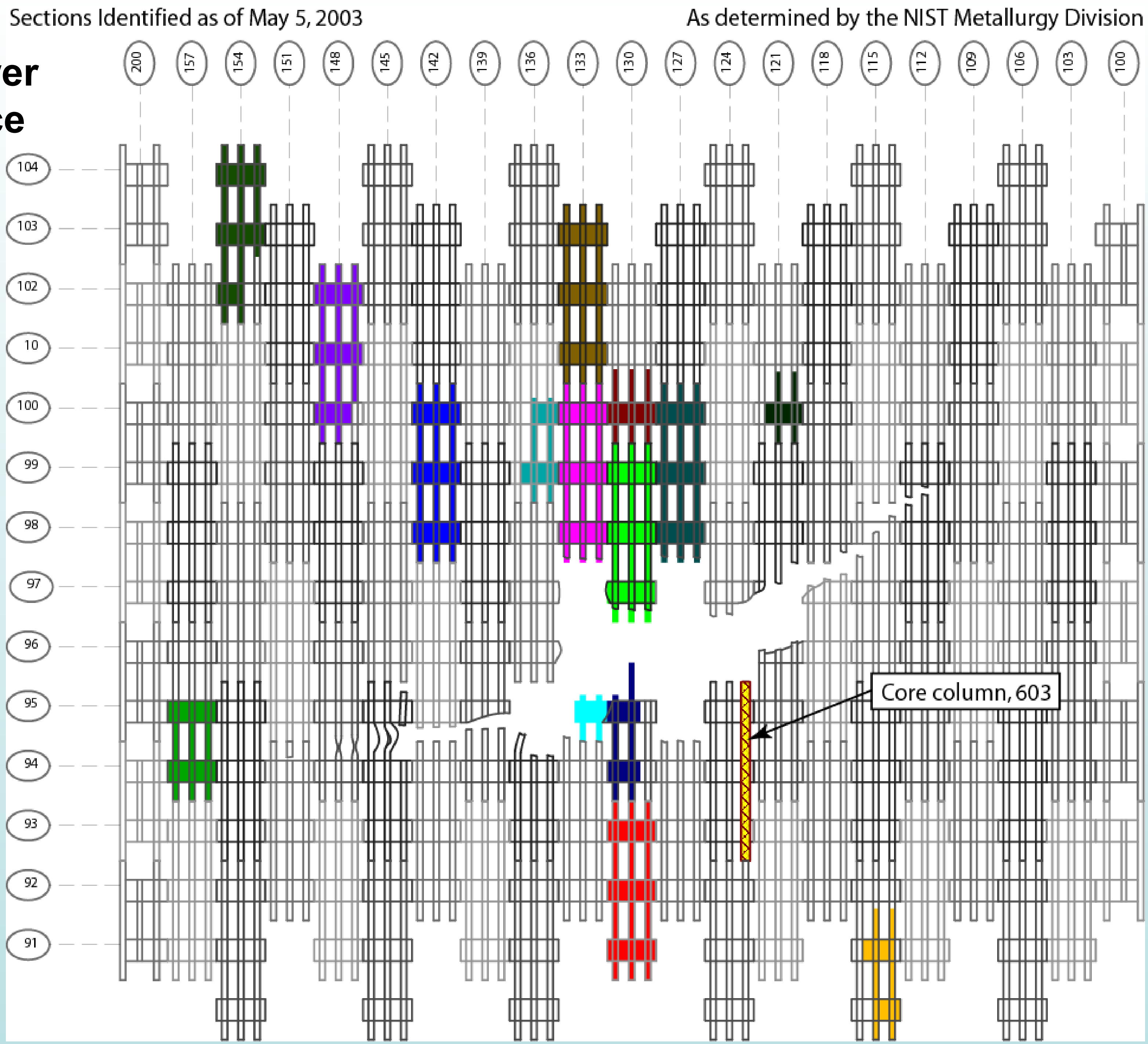
*Core box column*



*Core wide flange (WF) column*

# North Tower North Face

Identified perimeter panels



## 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

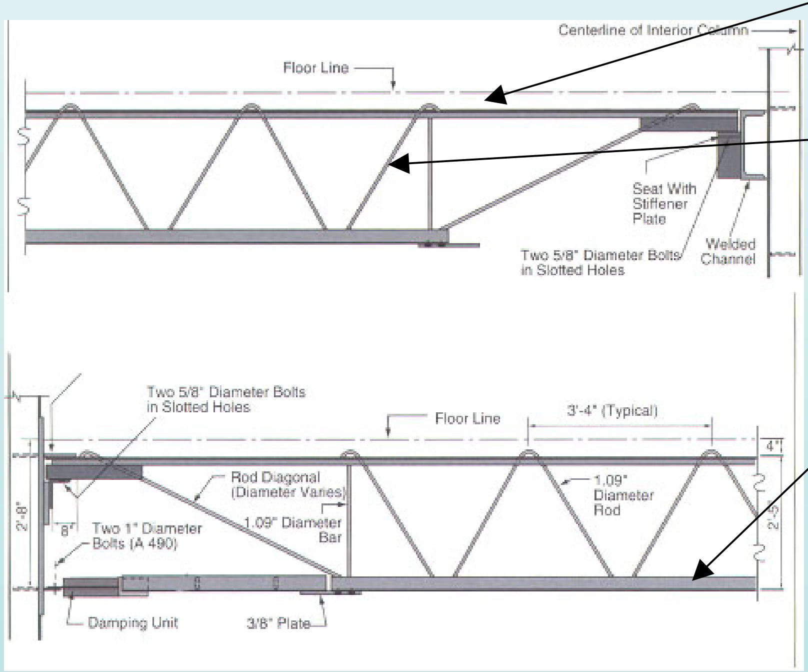
Analysis of these documents allow estimation of *typical* properties when specified *minimum* yield strength is known.

# Truss Properties – Laclede Steel

Supplier of approximately 50 truss variants of 60', 35', and bridging trusses

- *Supplier documents show where substitutions were made*

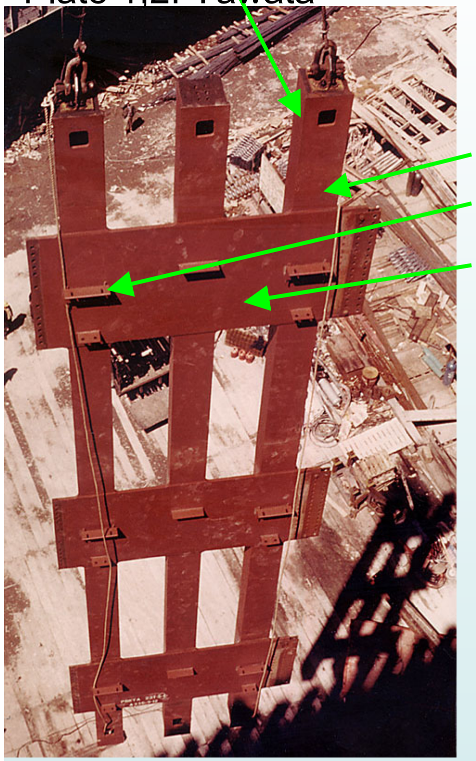
**Specified properties for 60' truss**




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

| Grade YS (ksi) | Estimated YS * (ksi) | Notes | Steel source / type |
|---|---|---|---|
| | | **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 pos 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.


CAUTION- DO NOT ENTER
CAUTION
EXIT

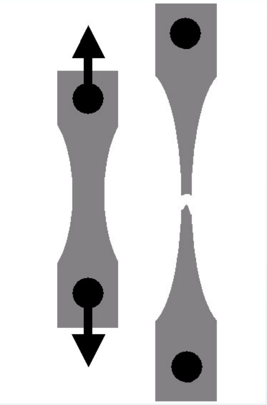
# Task 3 – Mechanical Property Determination

- **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

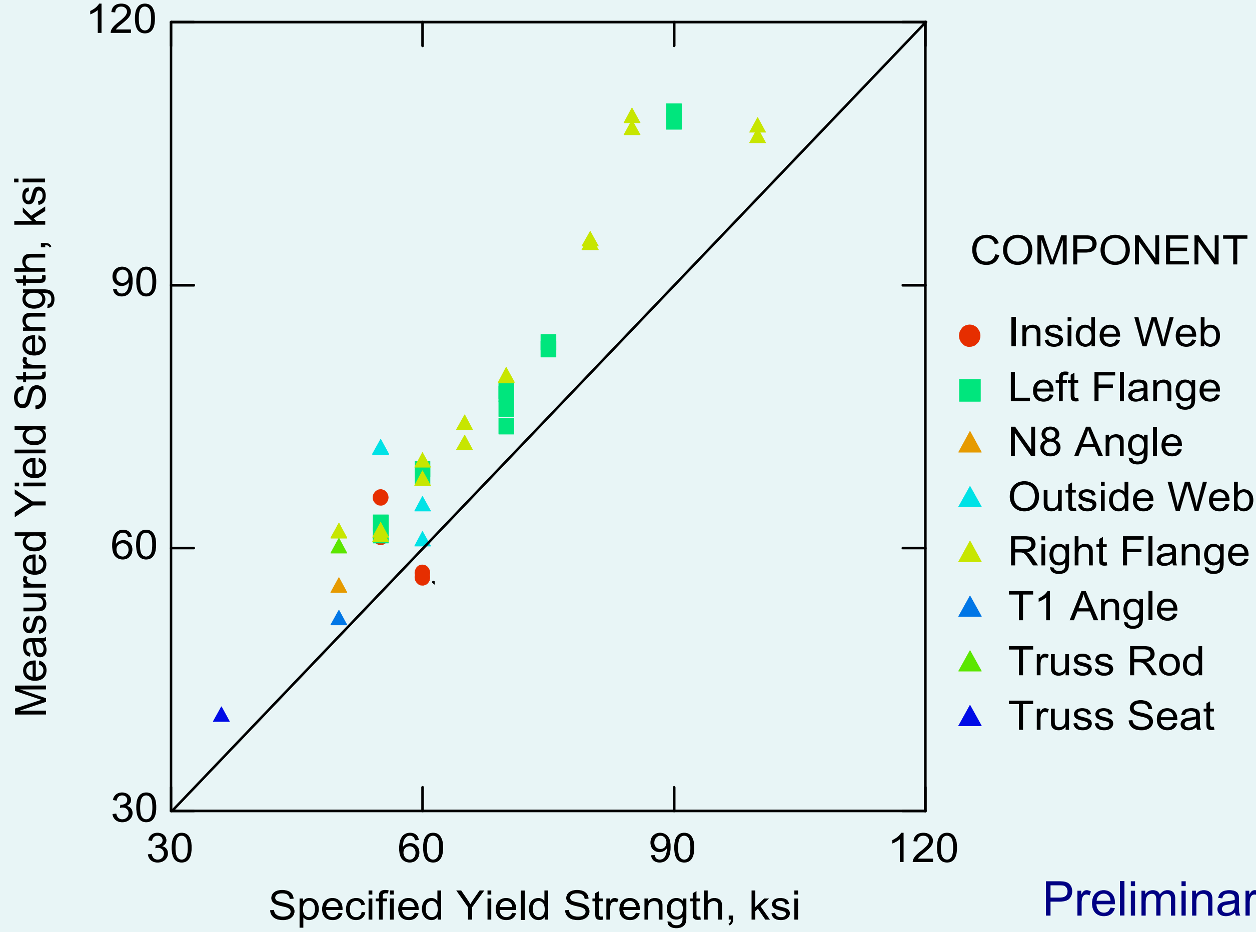
- Yield and ultimate strength, ductility and workhardening behavior (per ASTM A370 and E8)
- for comparison with specified properties
- for analyzing baseline structural performance

### 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*




Preliminary mechanical property data

*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

| Element | A36 angle | A242 Angle | A242 round |
|---|---|---|---|
| C (wt %) | 0.20 | 0.18 | 0.21 |
| Mn | 0.77 | 0.86 | 0.79 |
| P | 0.009 | 0.016 | 0.008 |
| S | 0.032 | 0.028 | 0.019 |
| Cu | 0.26 | 0.29 | 0.08 |
| V | 0.036 | 0.044 | 0.038 |
| N | 0.008 | 0.0066 | 0.008 |

## Mechanical Properties

| | | | |
|---|---|---|---|
| FY (ksi) | 57.6 | 60.3 | 60.0 |
| UTS (ksi) | 78.3 | 76.6 | 80.5 |

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

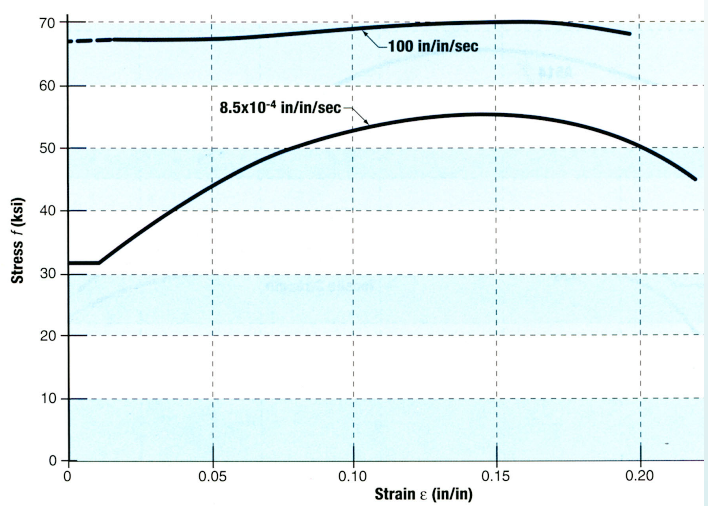



*Figure B-4 Effect of high strain rate on shape of stress-strain diagram (Tall 1974).*

- 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

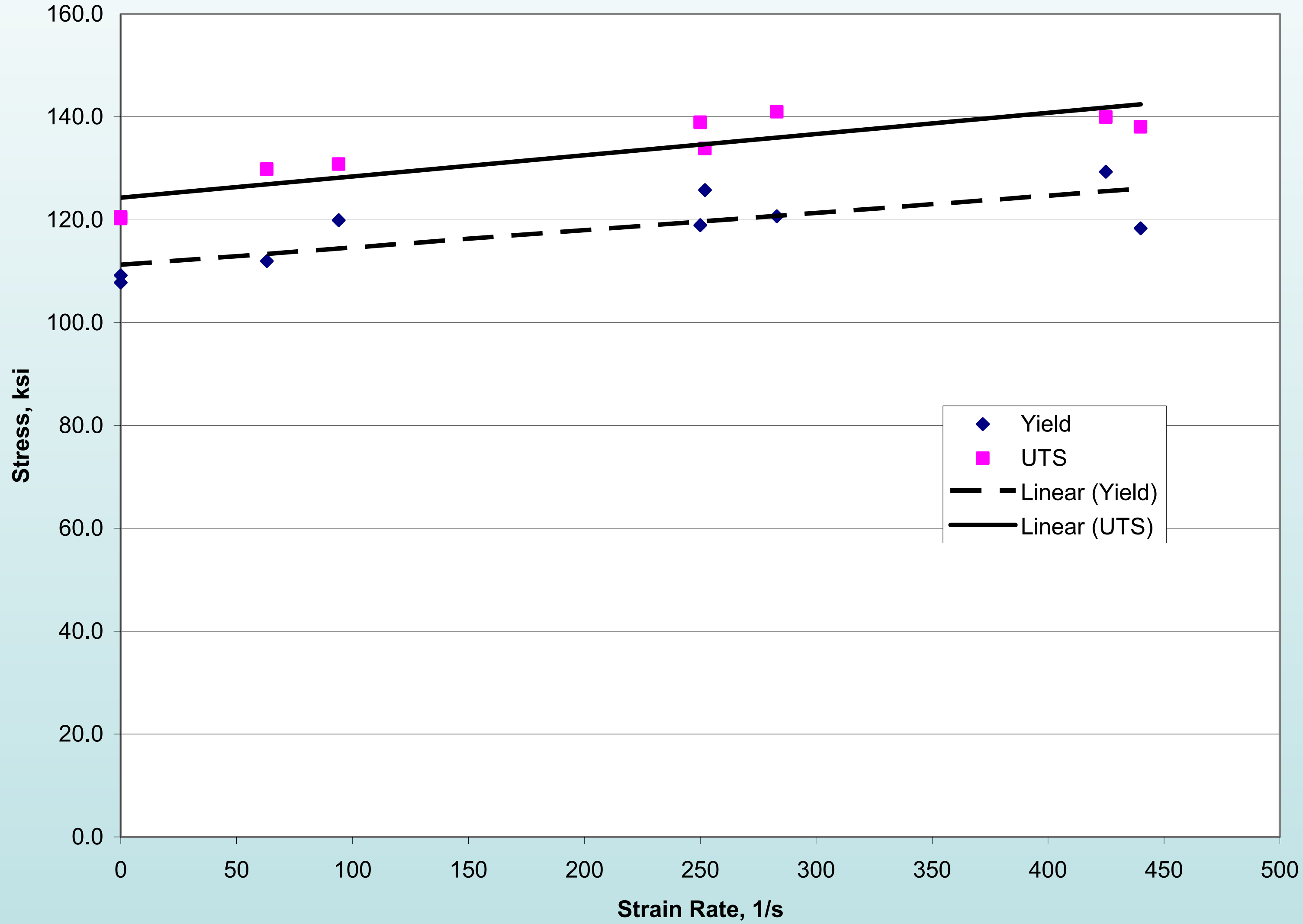

***Kolsky Bar setup***

# High Strain Rate Test Matrix

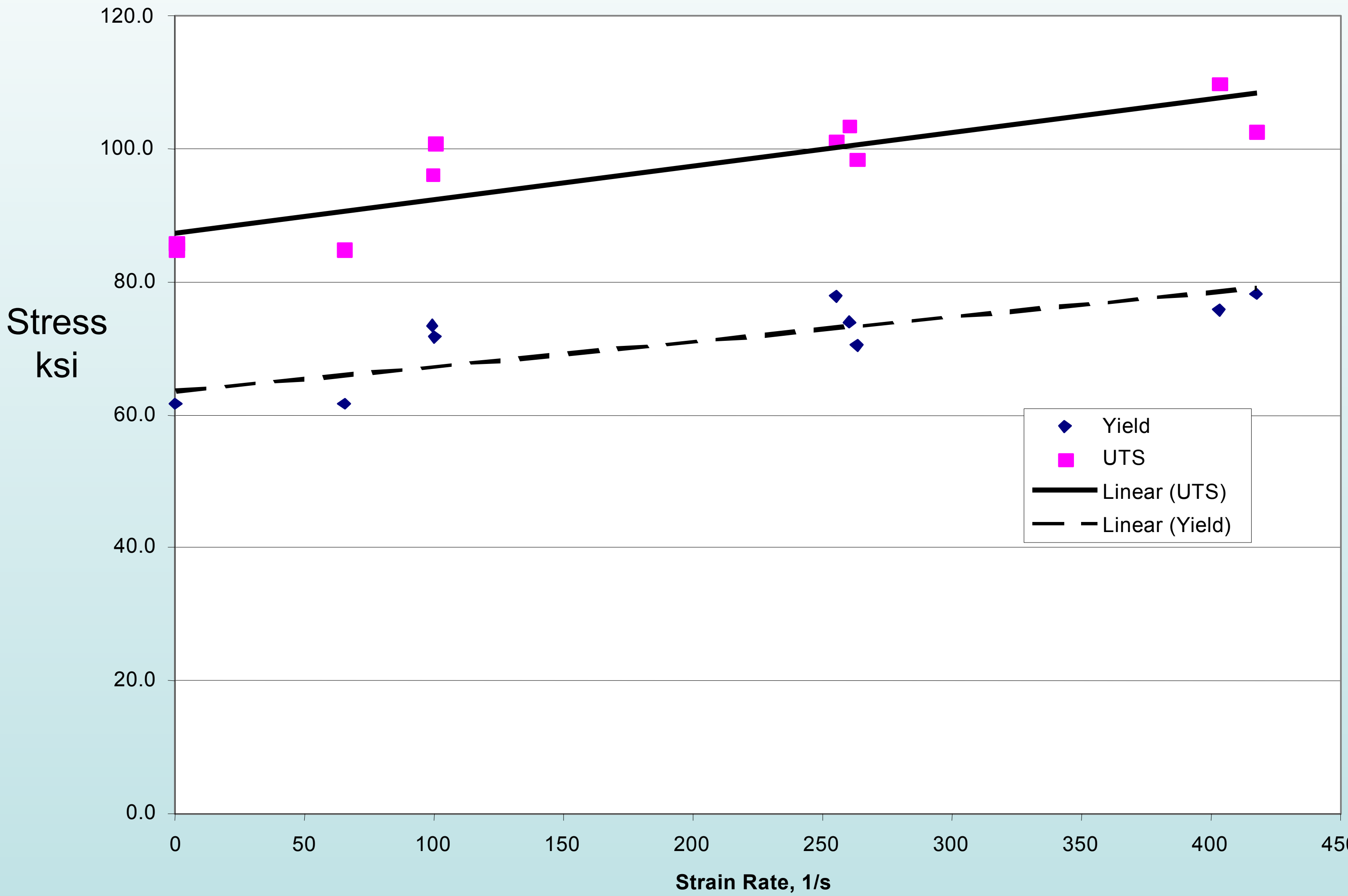
Grades of steel (duplicates) tested at each condition

| **Tensile test** | Strain rate | | |
|---|---|---|---|
| | 100 $s^{-1}$ | 300 $s^{-1}$ | 500 $s^{-1}$ |
| Outer Columns | 10 | 10 | 10 |
| Spandrels | 2 | 2 | 2 |
| Core columns | 2 | 2 | 2 |
| | | | |
| **Compression** | 500 $s^{-1}$ | 700 $s^{-1}$ | 900 $s^{-1}$ |
| Outer Columns | 10 | 10 | 10 |
| Spandrels | 2 | 2 | 2 |
| Core columns | 2 | 2 | 2 |
| Bolts | 1 | 1 | 1 |

# High Strain Rate Test Data



# High Strain Rate Test Data



# Elevated Temperature Properties

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

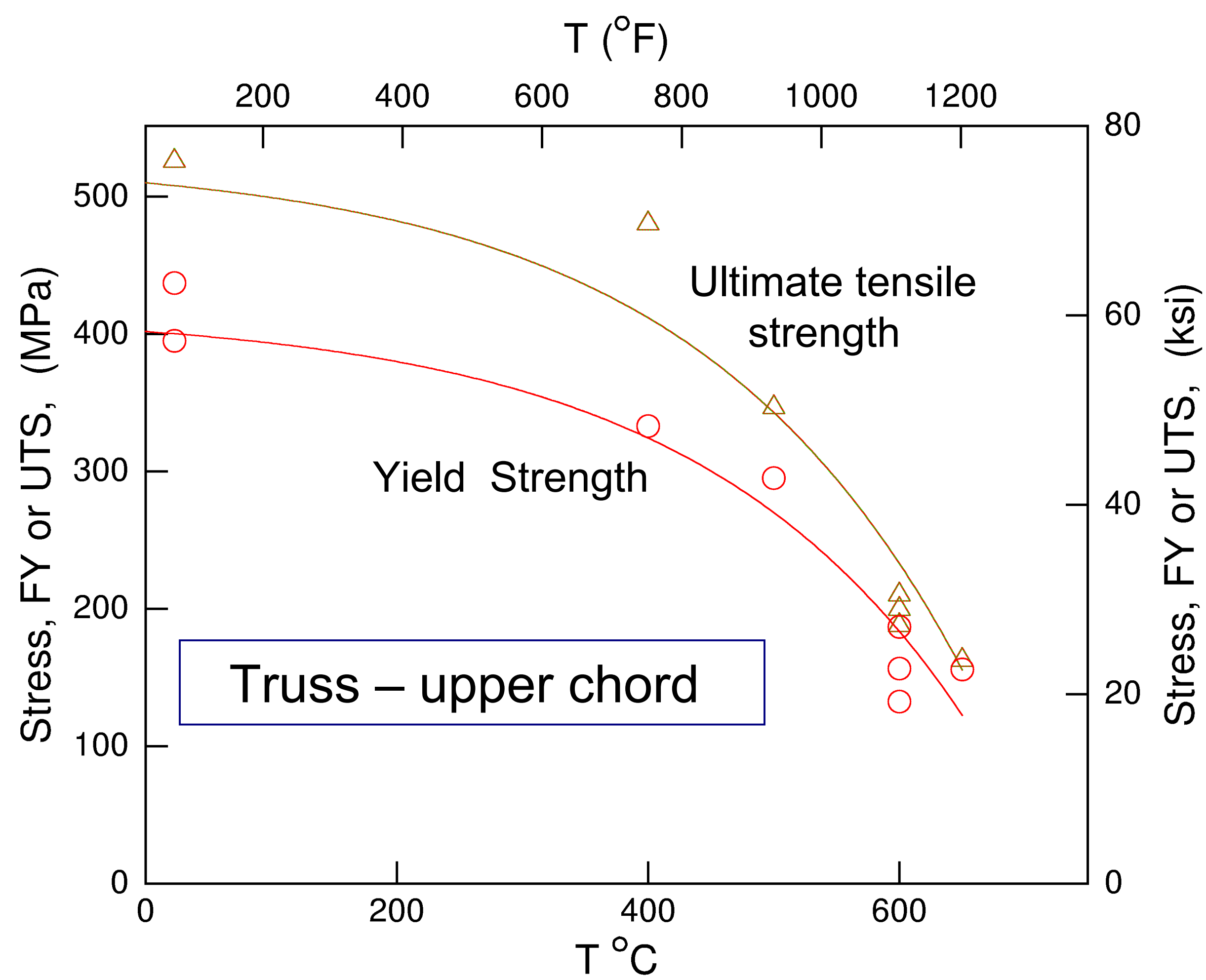
- **Hot Tensile Tests**
  - Yield, ultimate, ductility, workhardening
  - 400, 500, 600, 650 ºC
  - Strain rate is critical
  - Provides guidance for creep tests

- **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



# High Temperature Creep

Deformation under constant load

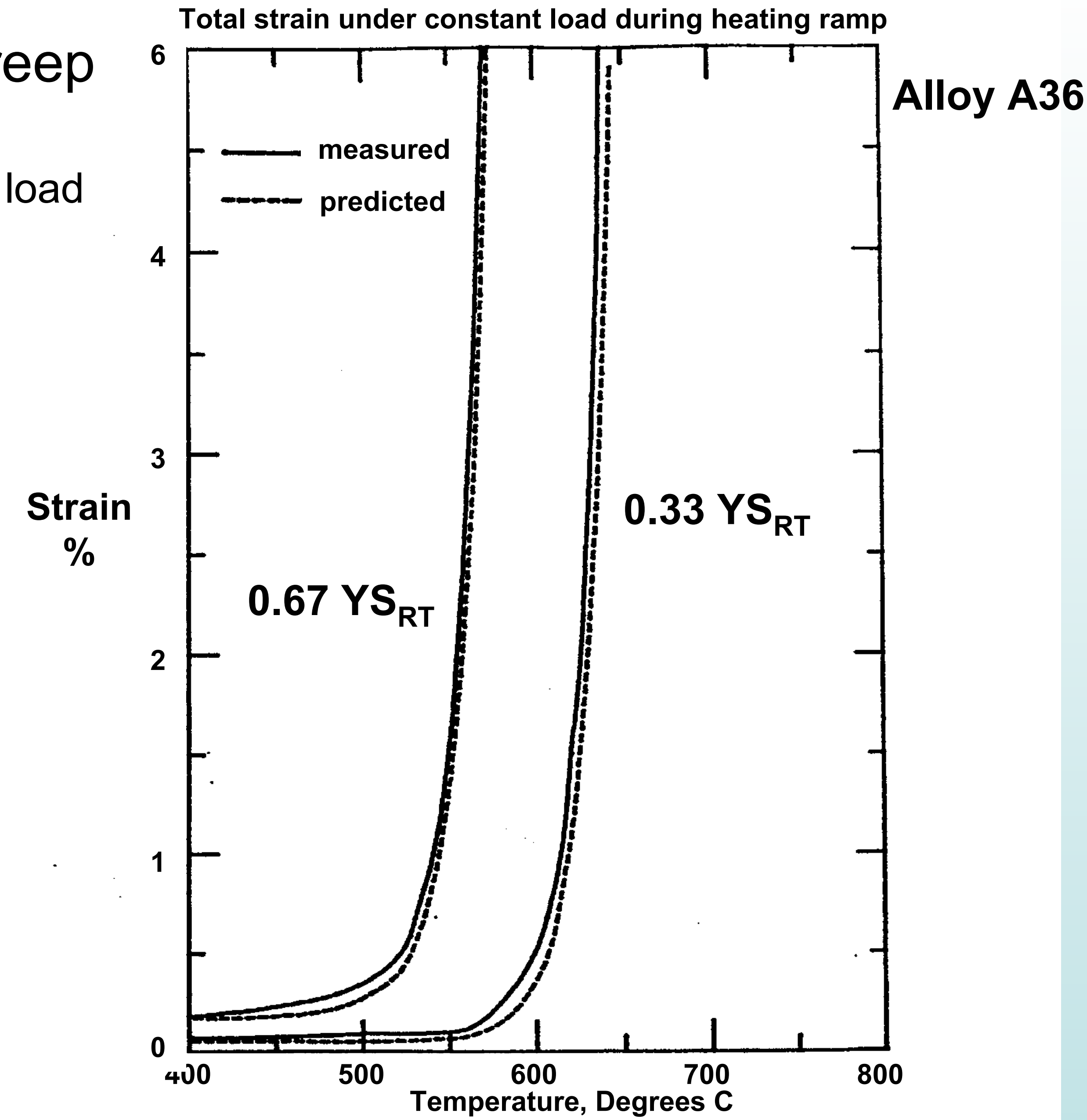
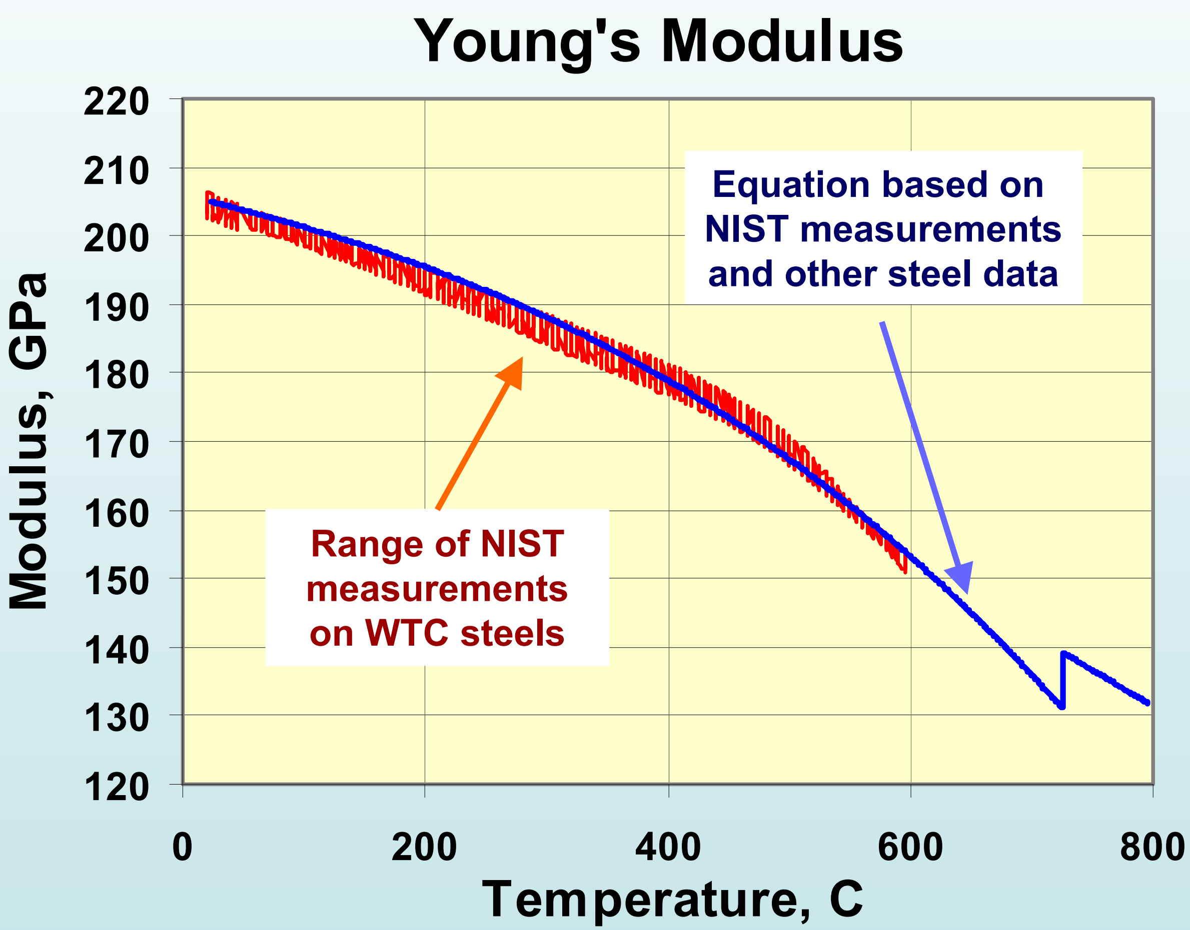



**Figure 11. Measured and predicted strains during a non-linear heating rate for stresses of 1/3 and 2/3 of the room temperature yield strength.**

Testing under way for:
- Core columns
- Perimeter columns
- Floor truss

# High Temperature – Elastic Modulus (stiffness)



# Current Status of Mechanical Test Program

| | % complete | Est. completion date |
|---|---|---|
| RT tensile tests (quasistatic) | 95% | 9/03 |
| High temperature tensile tests | 40% | 10/03 |
| Creep | 10% | 12/03 |
| High Strain Rate (tensile) | 75% | 10/03 |
| High Strain Rate (compression) | 50% | 10/03 |
| Welds | 30% | 12/03 |
| Bolts (tensile & High Strain Rate) | 75% | 9/03 |

*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