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

Condition of Thermal Insulation: Methodology

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Thermal-Structural Modeling

- Analysis of undamaged buildings exposed to postulated fires
- Analysis of damaged buildings exposed to 9/11 fires
- Condition of fireproofing needs to be characterized

Overview

- Sensitivity study
- In-place conditions
  - History of sprayed fire resistive material (SFRM)
  - Measurements
  - Statistical analysis
- Equivalent thickness
- Thermal properties
- Response to impact
- Summary


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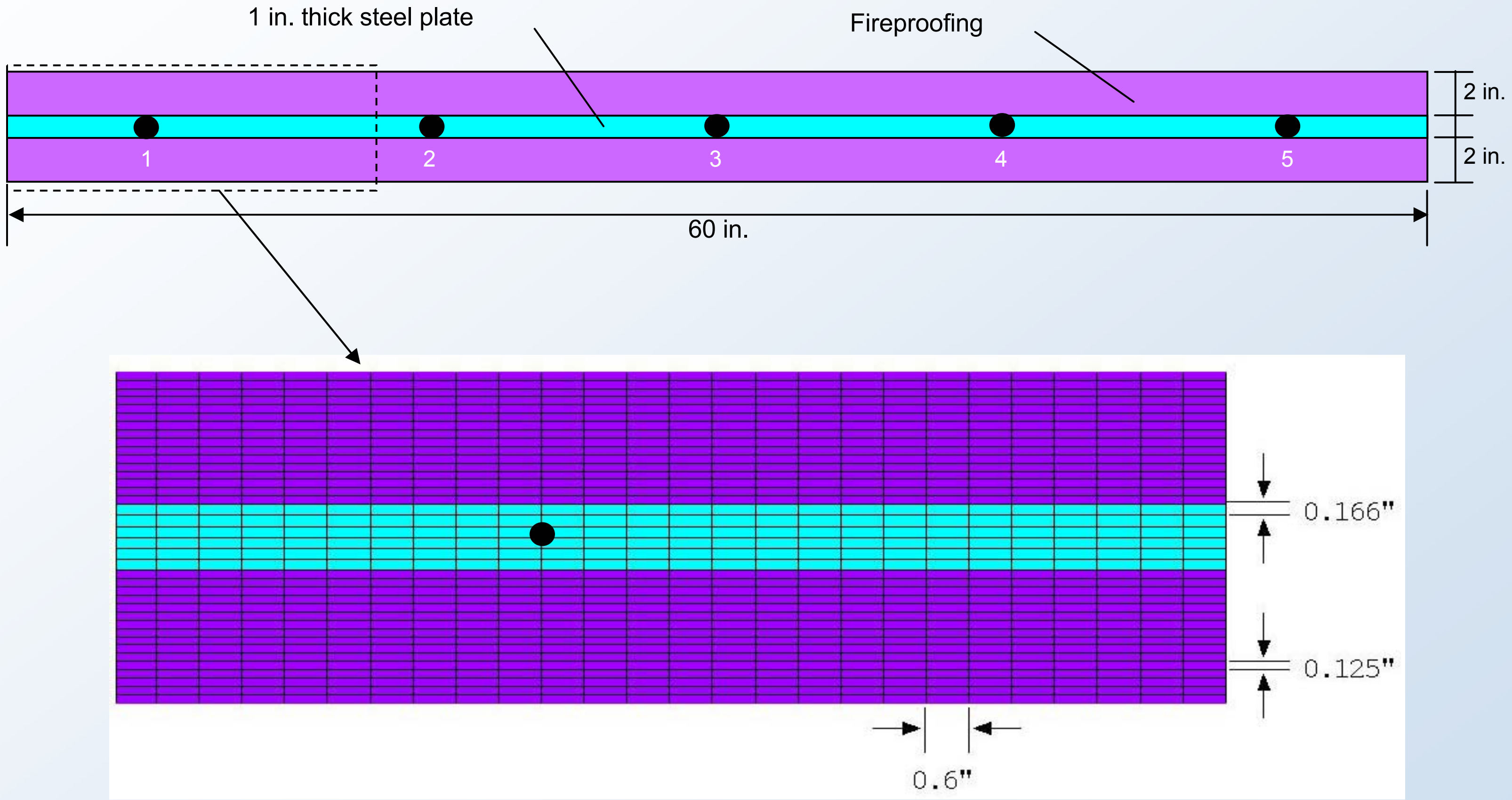
Sensitivity Study

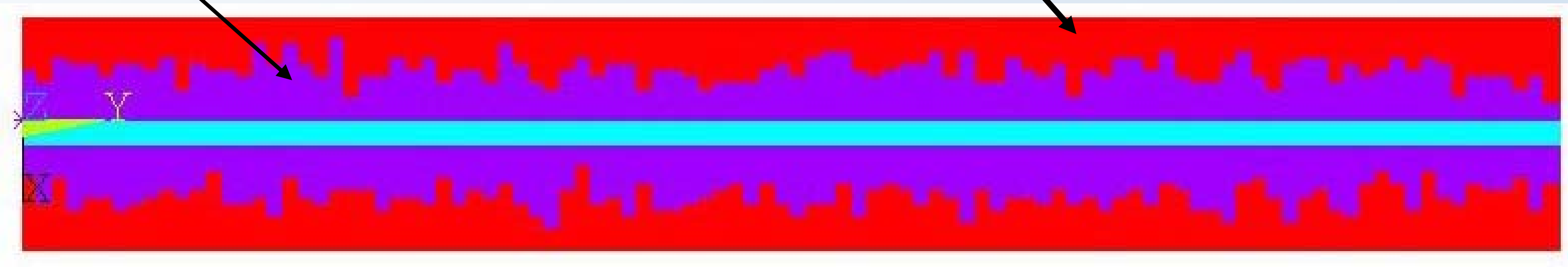
- Effects of thickness variability and "gaps" in SFRM
- Simplified finite-element analysis
  - 1 in. thick steel plate, 60 in. long
  - Average thickness: 0 to 2.0 in.
  - Standard deviation: 0 to 1.0 in.
  - Gap length: 0 to 30 in.
- Exposure: 1100 ºC fire
- Compute temperature history of steel

Model


1 in. thick steel plate
Fireproofing
2 in.
2 in.
1
2
3
4
5
60 in.
0.166"
0.125"
0.6"

Model

- Use psuedo-random number generator to select SFRM thickness at cross-section
  - Based on average thickness and standard deviation



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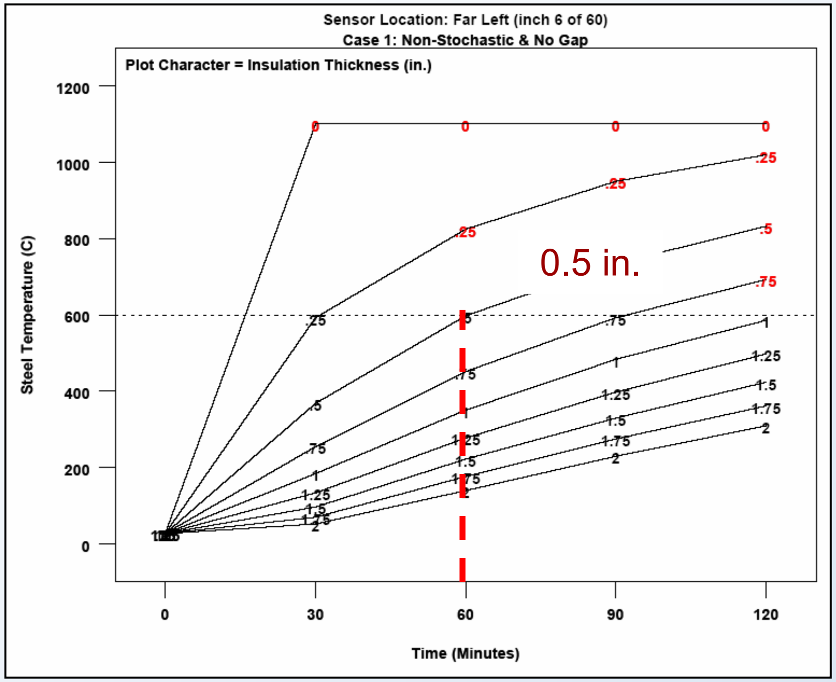
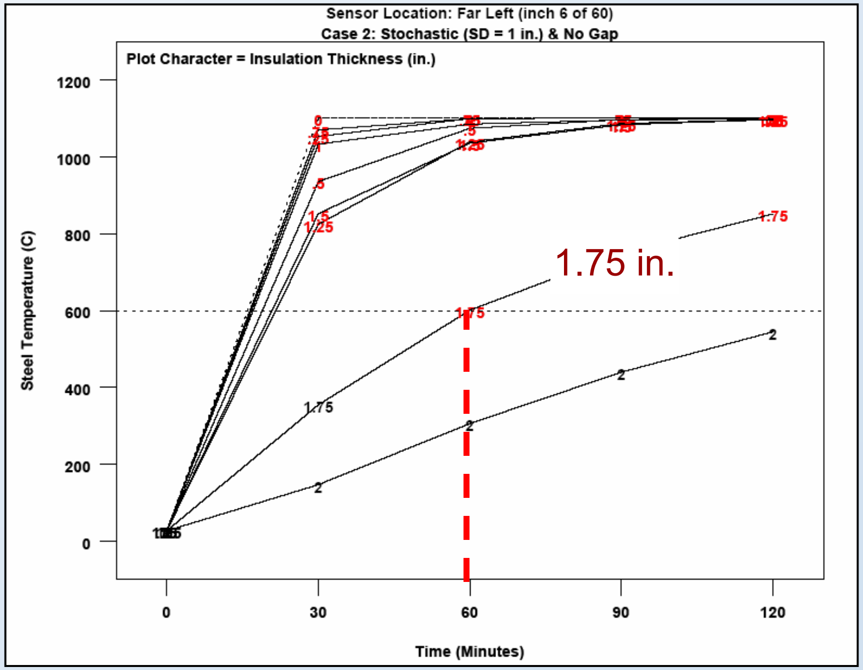
Example

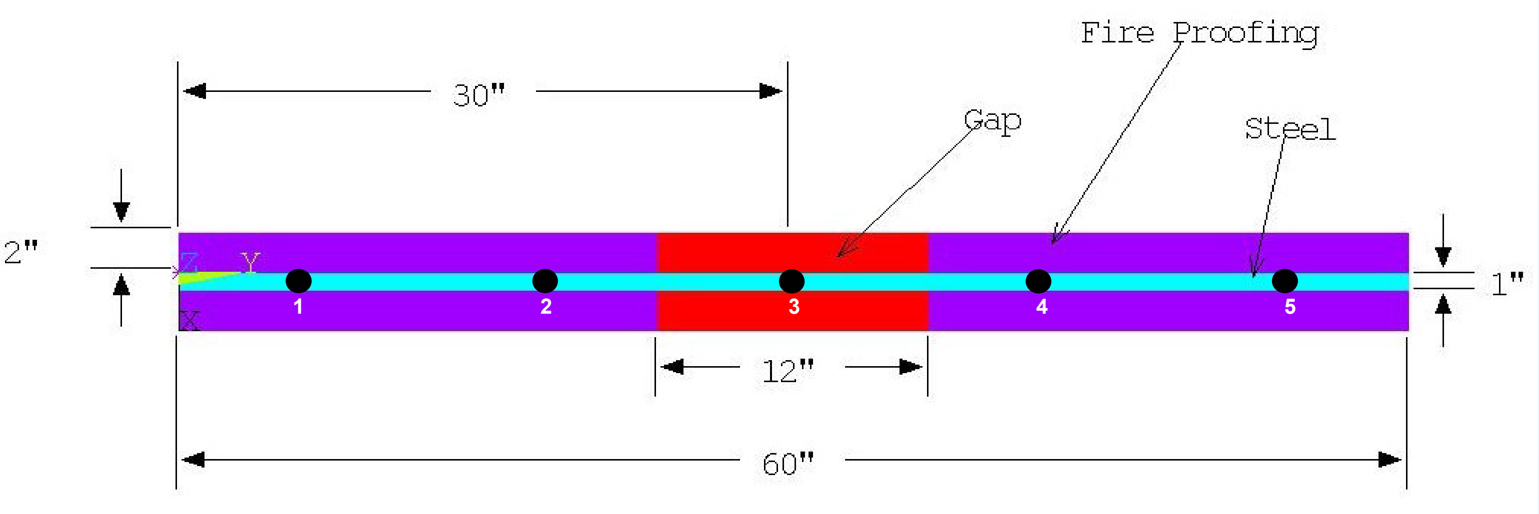
Uniform Thickness



Standard Deviation = 1 in.

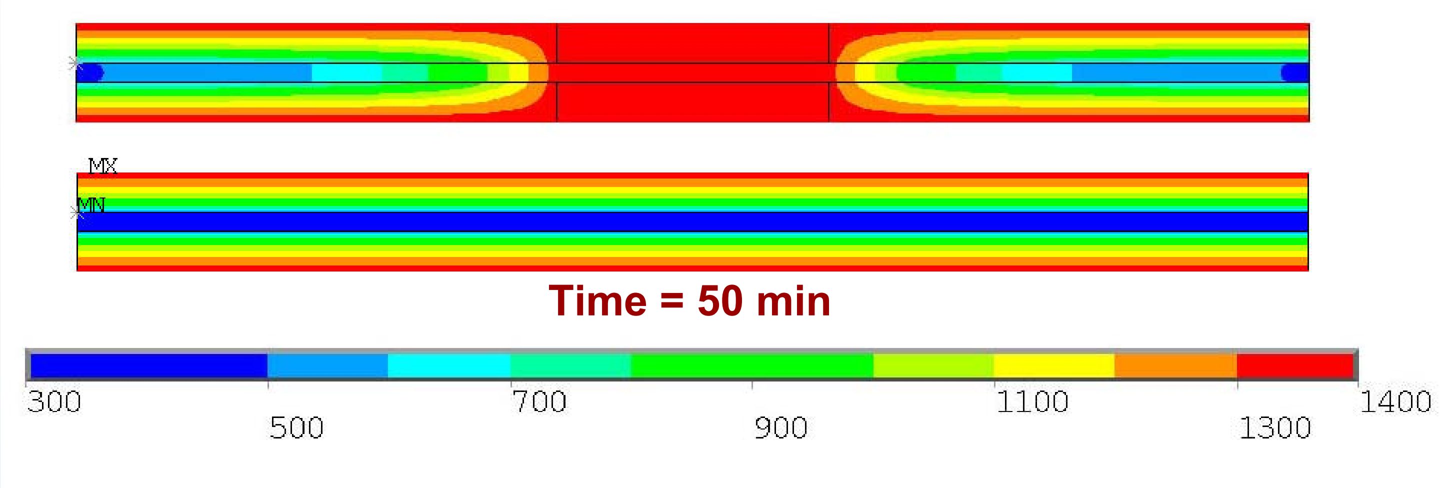


Effect of Gap in SFRM



With Gap

No Gap



Sensitivity Study

- Variability in thickness of SFRM reduces its effectiveness
- Gap in SFRM:
  - Local heating
  - Path for heat flow into member

History of SFRM in WTC Towers

- 1969: Decision to use ½ in. CAFCO® BLAZESHIELD ® Type D
- 1970: CAFCO® BLAZESHIELD® Type D discontinued at 38th floor, replaced with CAFCO® BLAZESHIELD® Type D/CF
- 1994: Thickness measurements on floor trusses on 23rd and 24th floors
- 1995: PA initiated study of SFRM thickness during tenant alterations
- 1999: PA established guidelines for SFRM replacement and repair
- Late 90s: SFRM upgraded to 1 ½ in. with CAFCO® BLAZESHEILD® Type II

Specified Thickness

- October 30, 1969 PA Correspondence
  - Columns < 14WF228: 2 3/16 in.*
  - Columns ≥ 14WF228: 1 3/16 in.
  - Beams, spandrels, floor trusses: ½ in.
- Alcoa Drawings (Note 11)
  - 3 h on spandrels ½ in. 1/2 in. V.A.**
  - 4 h on columns (heavy) 1 3/16 in. 7/8 in. V.A.
- 1995 Upgrade Study
  - Floor trusses 1 ½ in.

*CAFCO® BLAZESHIELD® Type D
**V.A. = Vermiculite aggregate plaster

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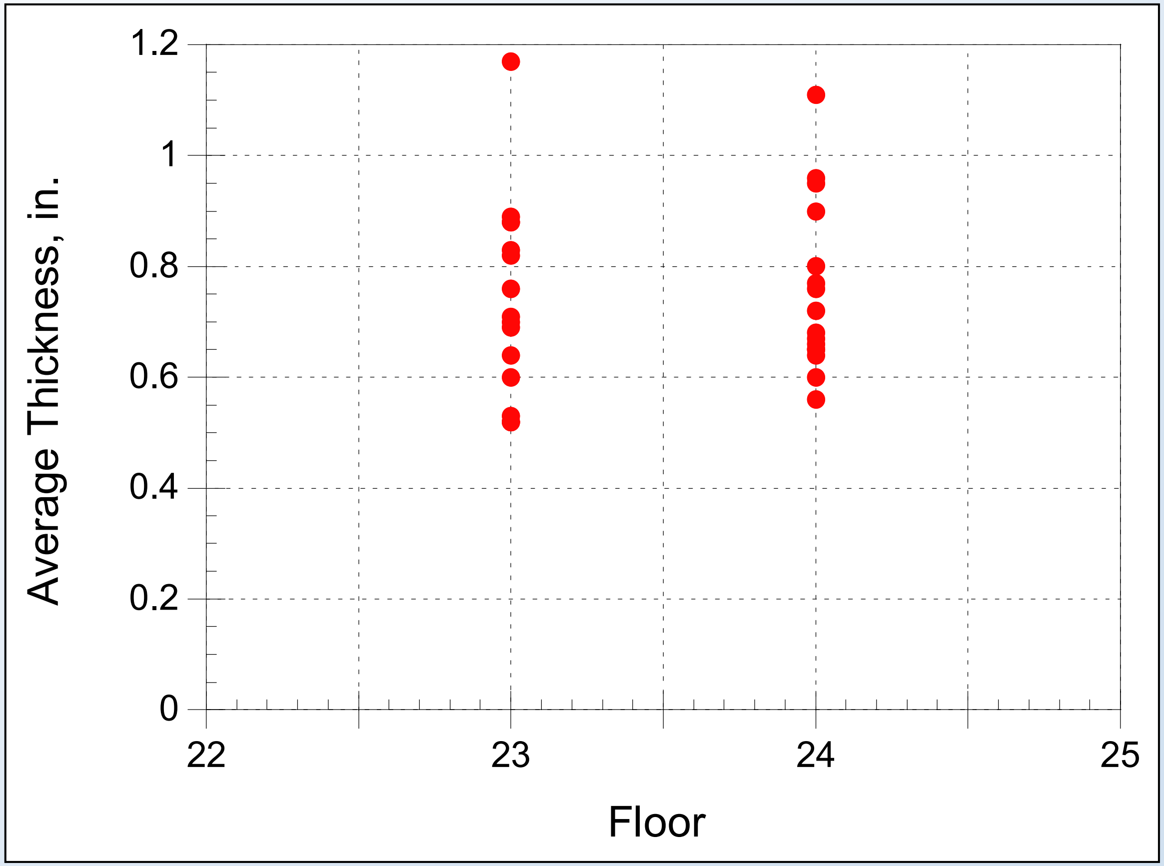
Thickness Measurements

- 1994 measurements on 23rd and 24th floors of WTC 1
- Analysis of photographs taken in the 1990s
- Thickness measurements in PA Construction Audit Reports from late 1990s
- 1999 measurements of beams and columns in WTC 1 shaft 14/15

Floors 23 and 24 Trusses (1994)

- 16 randomly selected trusses per floor
- 6 replicate measurements on “flanges and web”

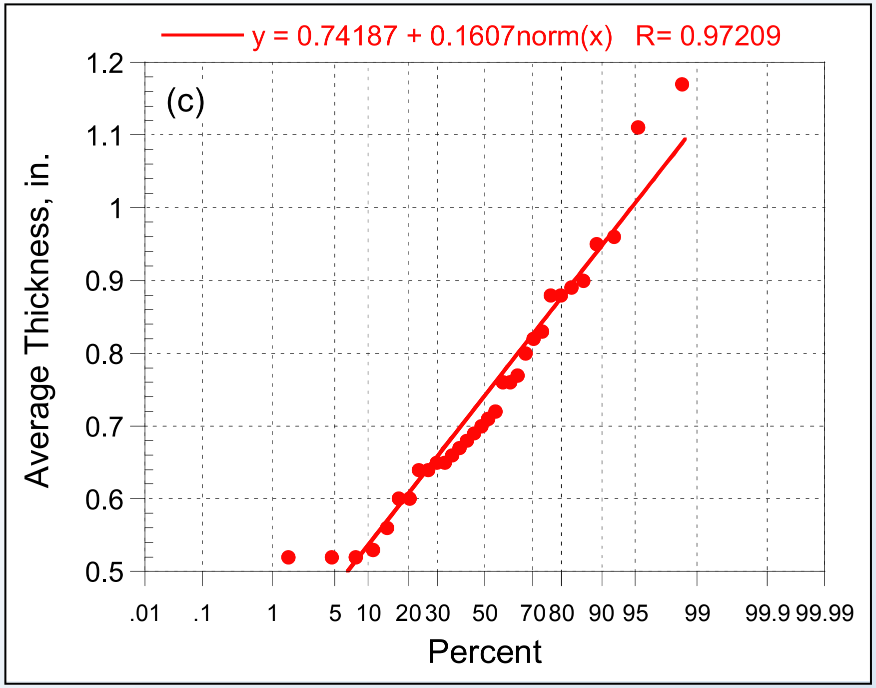
Grand Average = 0.74 in.
St. Dev. of Avg. = 0.16 in.



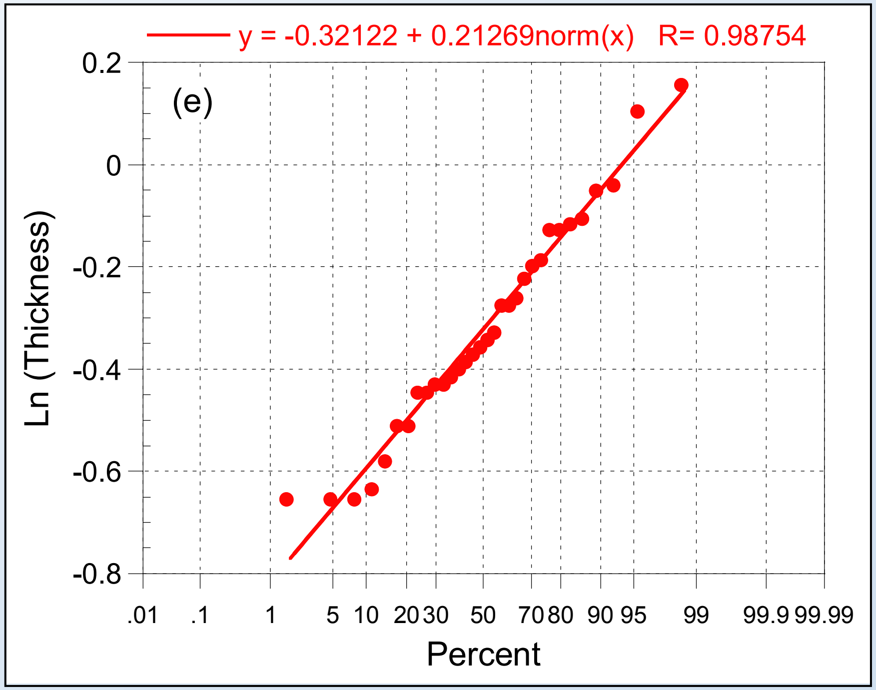
Normal Probability Plots

- Thickness appears better described by log-normal distribution

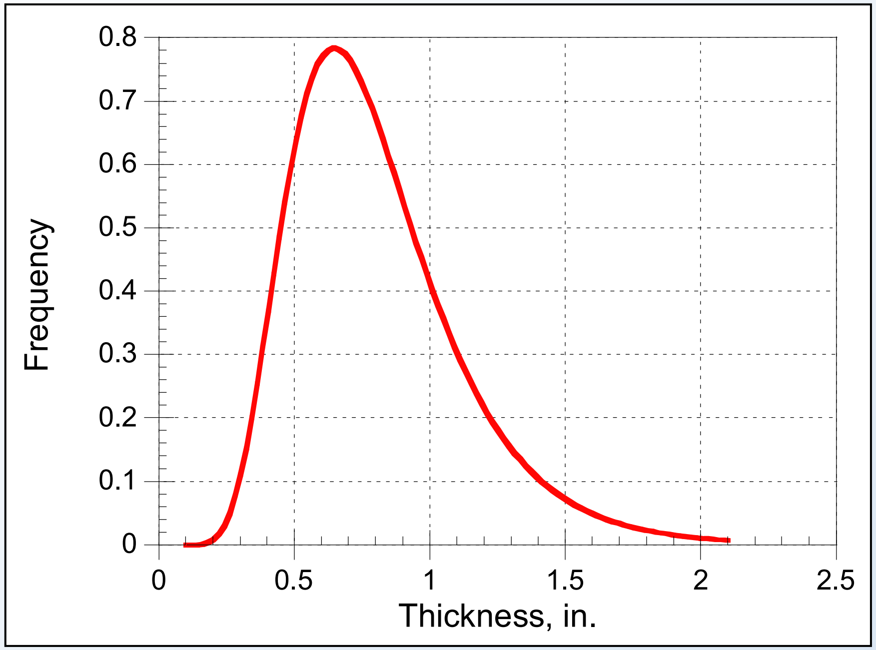
Thickness

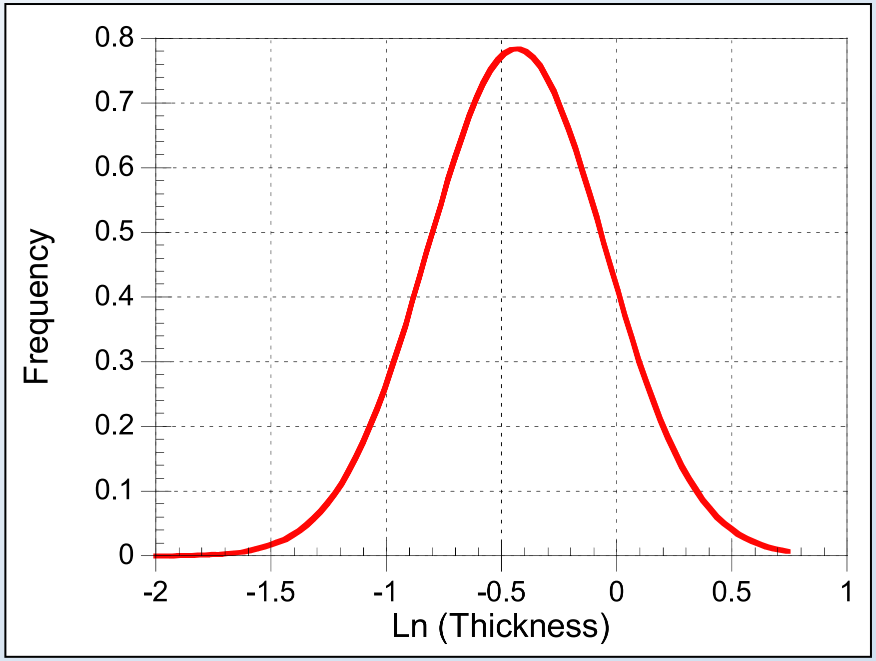


Natural Logarithm of Thickness



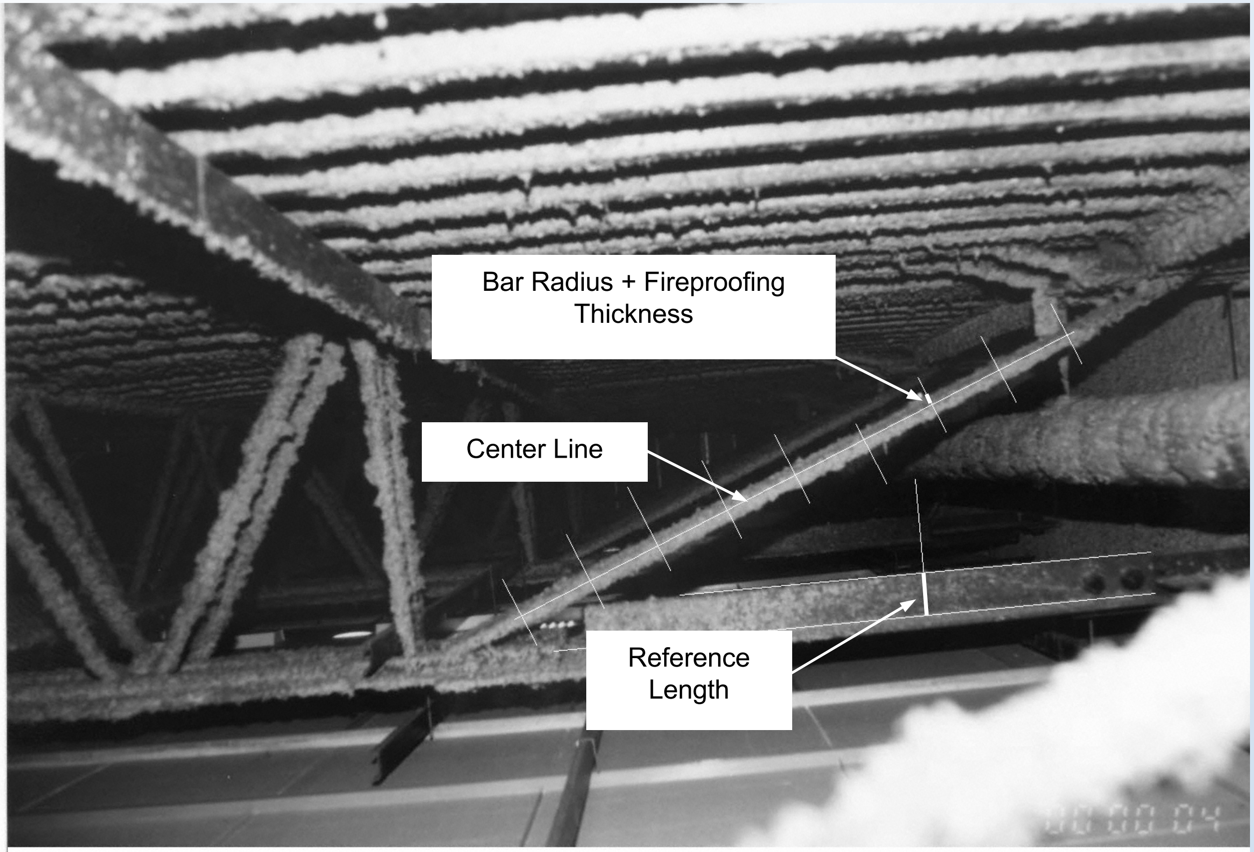
Lognormal Distribution





Analysis of Photographs

- Original SFRM: WTC 1 (22, 23, 27) in mid 1990s
- Upgraded SFRM, WTC 1 (below 31) in 1998



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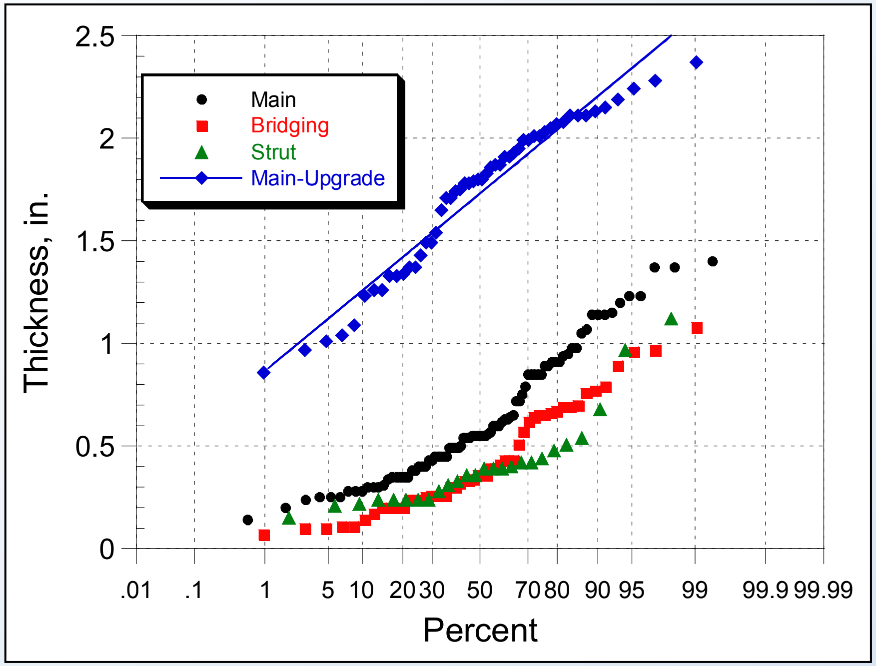
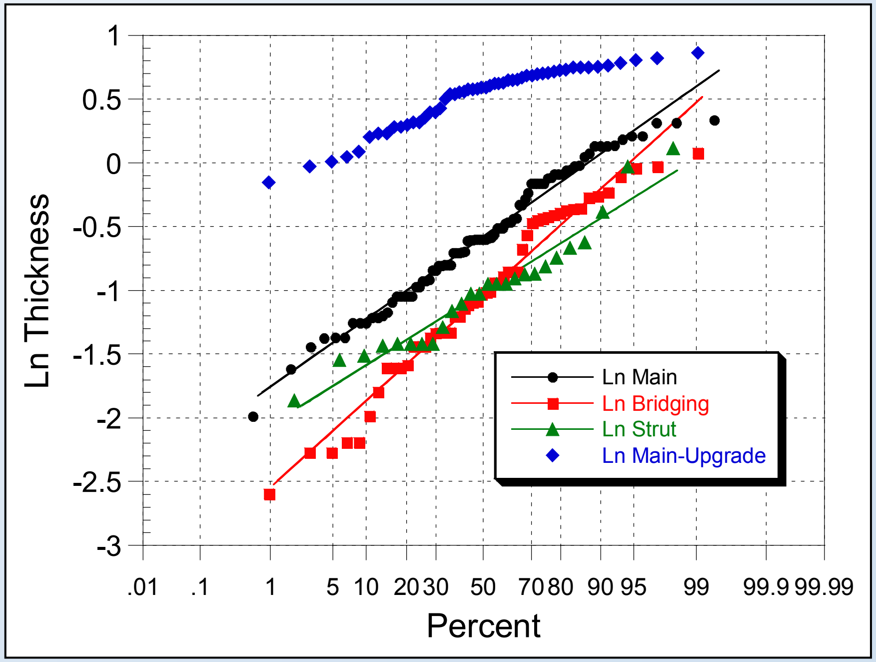
Results of Photo Analysis

- Original SFRM thickness distribution appears to be lognormal
- Upgraded SFRM thickness distribution appears to be normal



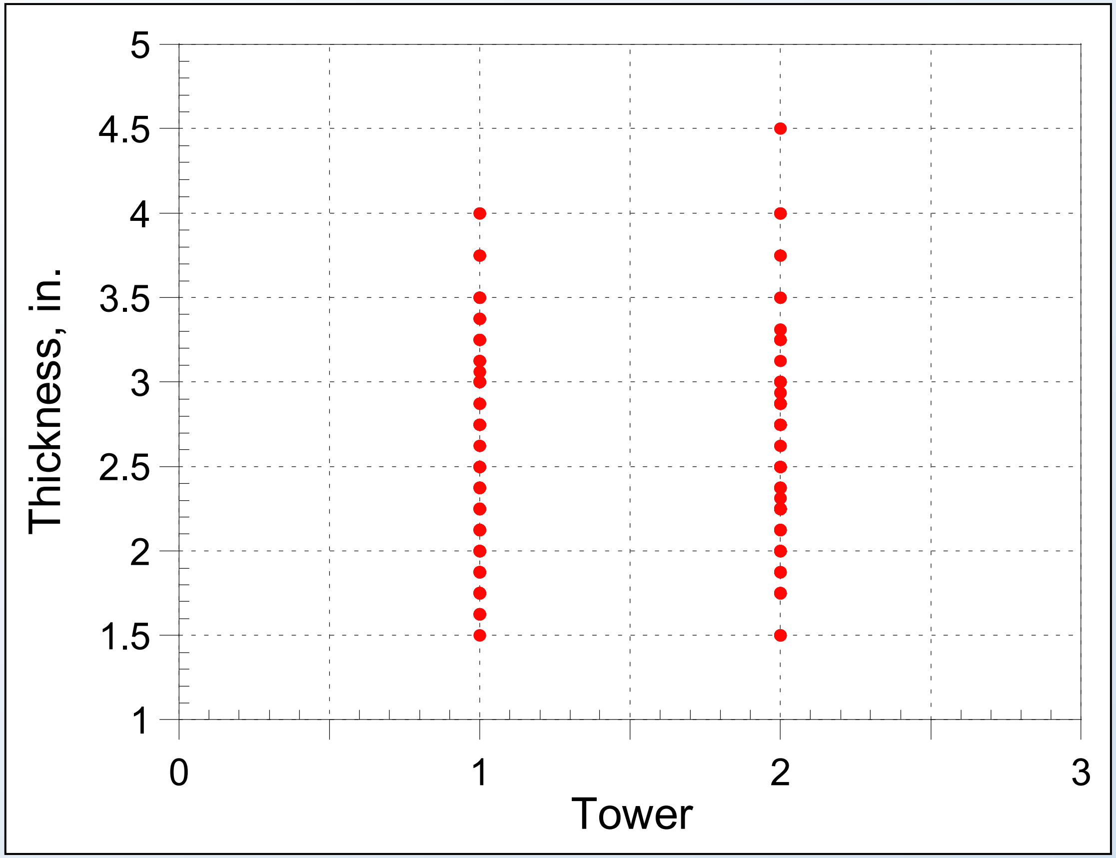


Summary of Photo Analysis

Floor Truss	Average Thickness	Std. Dev.	Coeff. of Variation
Original Main	0.6 in.	0.3 in.	0.5
Original Bridging	0.4 in.	0.25 in.	0.6
Original Strut	0.4 in.	0.2 in.	0.5
Upgraded Main	1.7 in.	0.4 in.	0.2

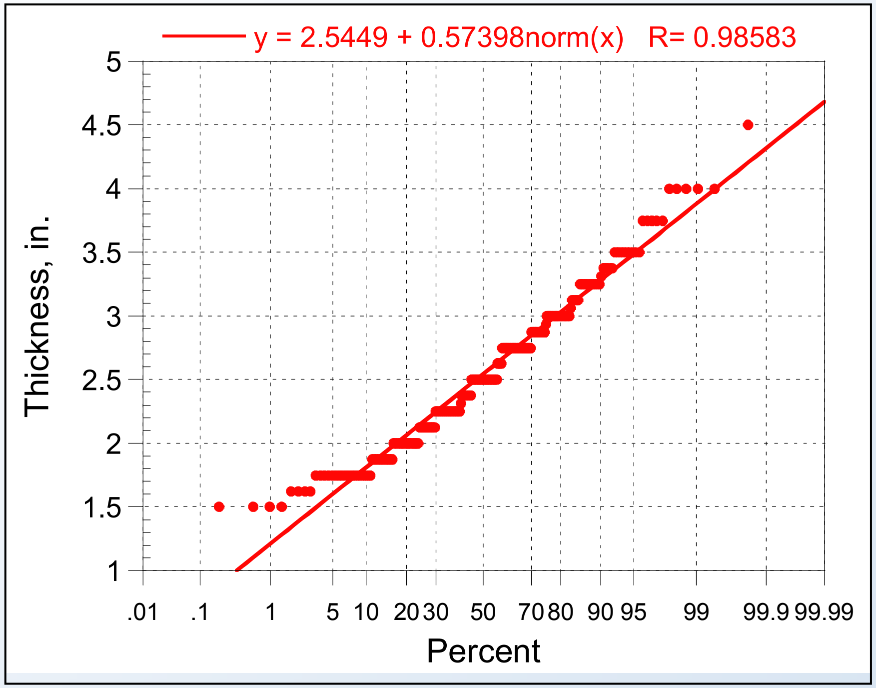
Construction Audit Reports

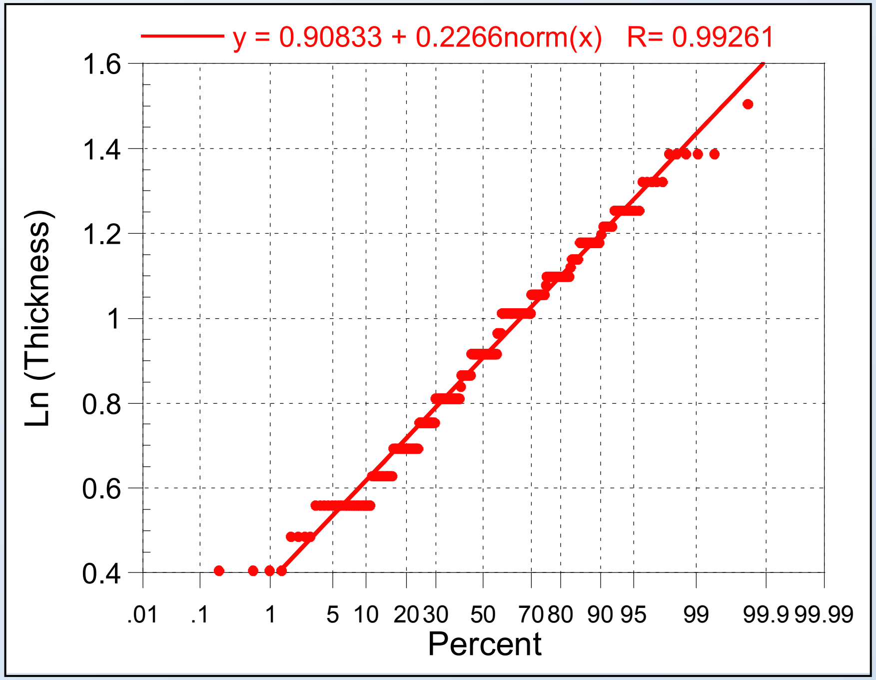
- 18 data sets for WTC 1 (93, 95, 98, 99 and 100)
- 14 data sets for WTC 2 (77, 78, 88, 89, 92)



Combined Measurements

- Lognormal distribution appears more appropriate
- Overall average = 2.5 in.
- Overall standard deviation = 0.6 in.





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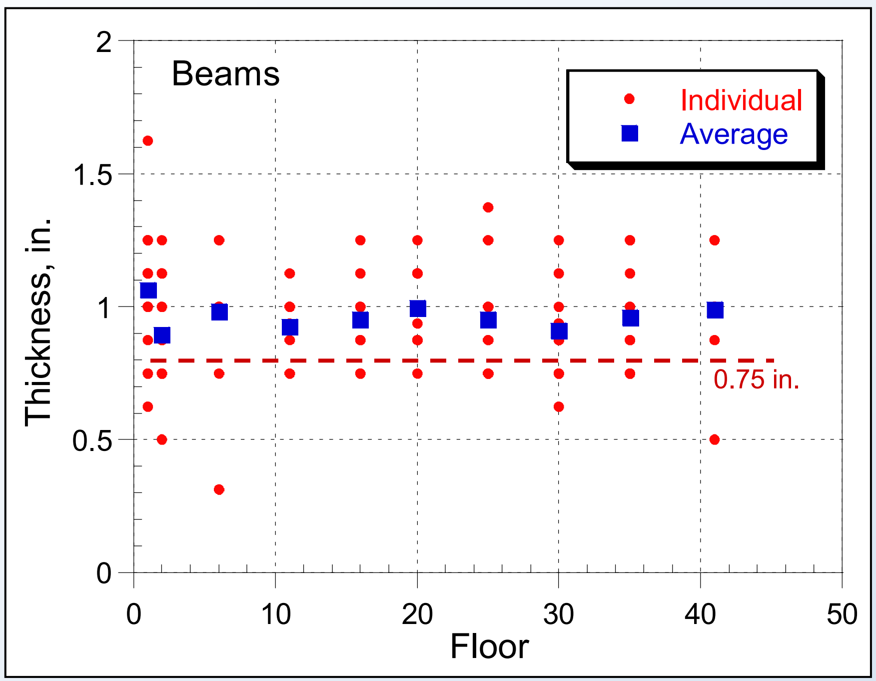
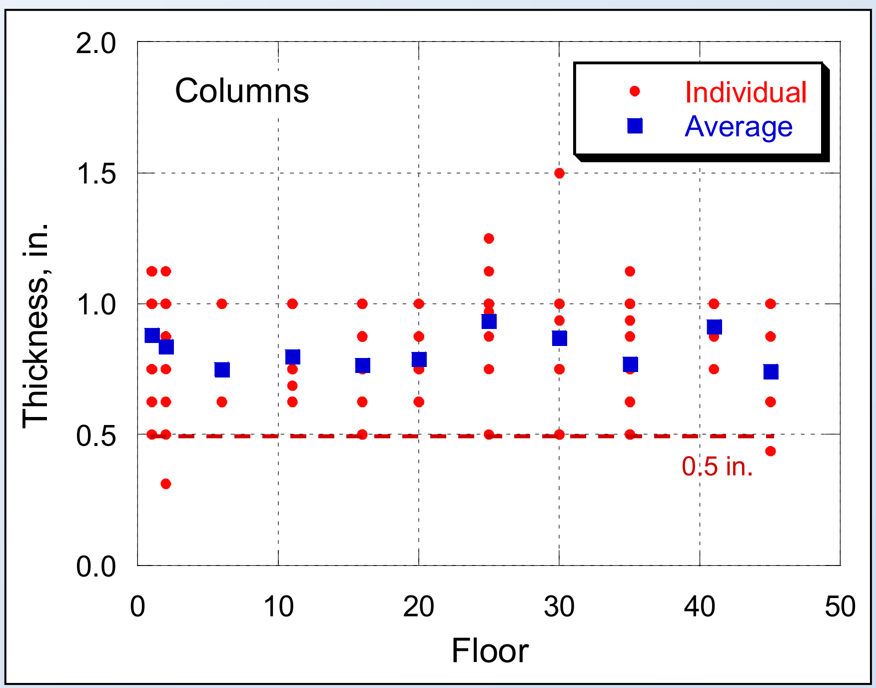
Core Beams and Columns

- April 1999 measurements in shaft 14/15 of WTC 1 (1st to 45th floor)

Average = 1.0 in.
St. Dev. = 0.2 in.



Average = 0.8 in.
St. Dev. = 0.2 in.



Summary of SFRM Thickness

Data Source	Element	Average	St. Dev.	Coeff. of Variation
PA Measurements	Truss	0.7 in.	0.2 in.*	0.2*
Photos	Main Truss Brdg. Truss Strut Main Upgraded	0.6 in. 0.4 in. 0.4 in. 1.7 in.	0.3 in. 0.25 in. 0.2 in. 0.4 in	0.5 0.6 0.5 0.2
PA Measurements	Truss Upgraded	2.5 in	0.6 in.	0.2
PA Measurements	Core Beams Core Columns	1.0 in. 0.8 in.	0.2 in. 0.2 in.	0.2 0.25

*Variability of averages

Equivalent Thickness

- Variability of thickness reduces effectiveness of SFRM
- Not practical to include variable thickness in thermal modeling
- Establish "equivalent uniform thickness" that provides thermal protection equivalent to variable thickness
- Approach
  - Bar model with variable thickness SFRM
  - Compute elongation under 12,500 psi tensile stress as a function of time
  - Compare with elongation obtained with uniform thickness SFRM

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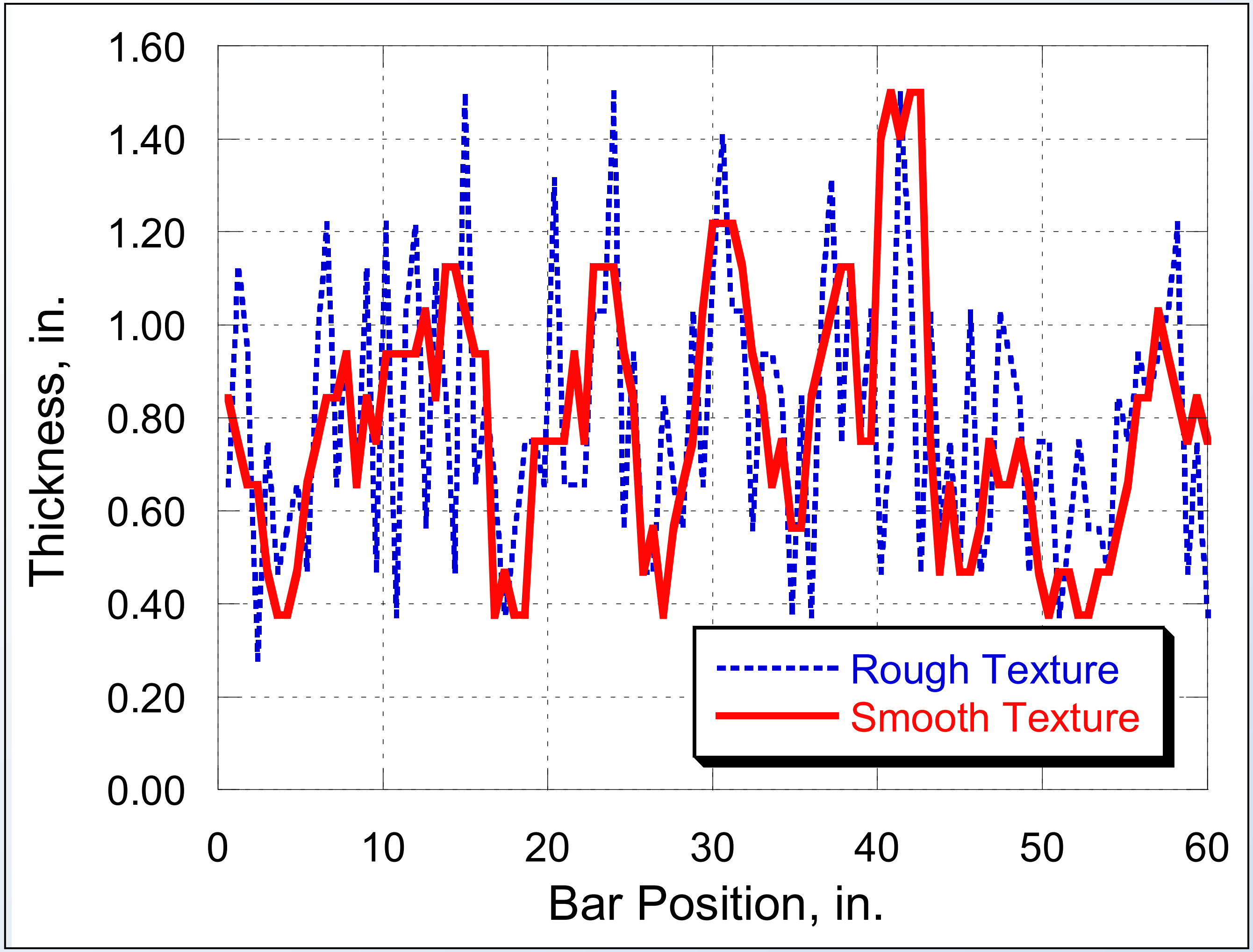
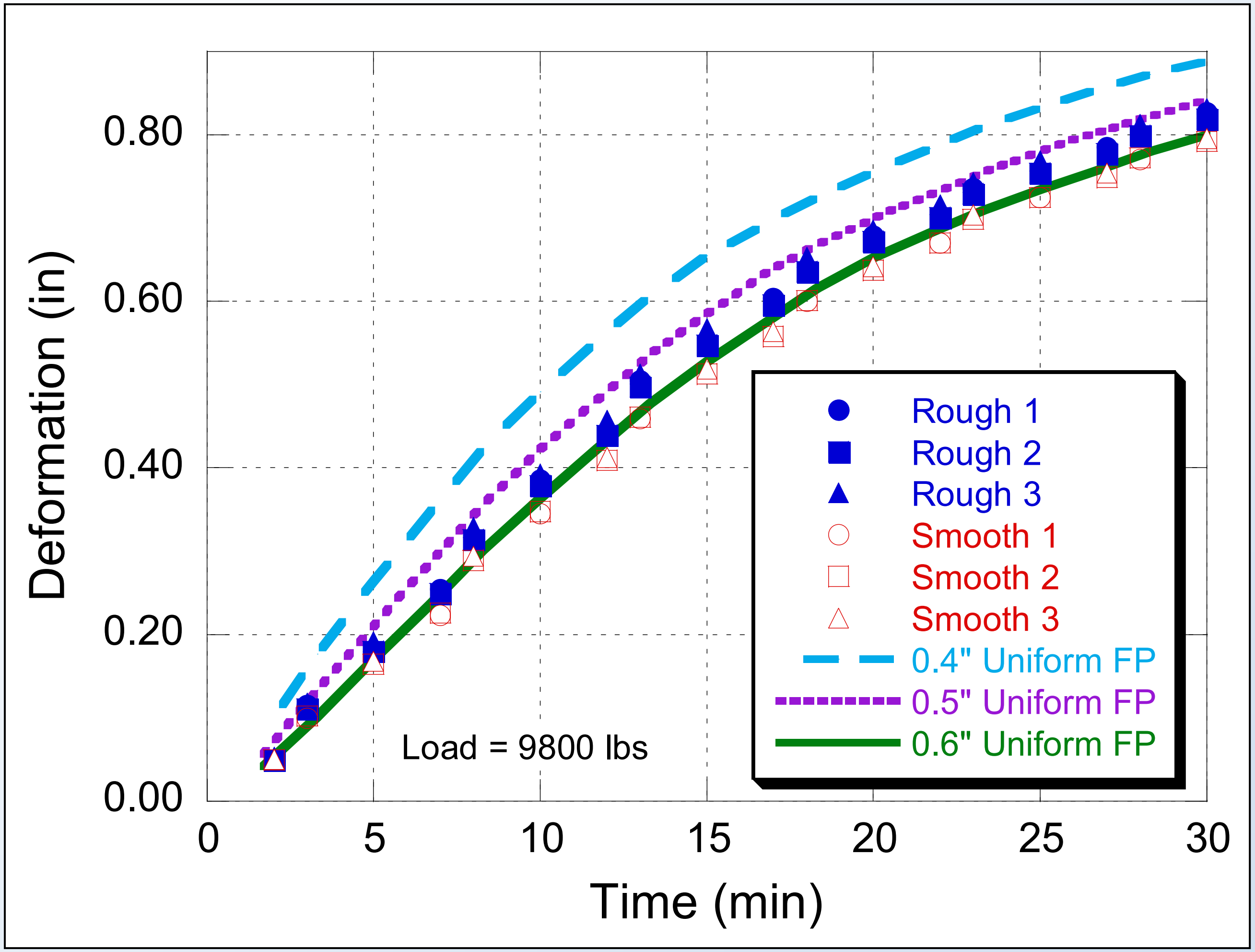
Cases Considered (Floor Truss)

- Lognormal distribution
- Original SFRM: t_{avg} = 0.75 in., st. dev. = 0.3 in.
- Upgraded SFRM: t_{avg} = 2.5 in., st. dev. = 0.6 in.
- 3 sets of psuedo-random numbers
- 100 elements for 60 in. bar
- 5-point smoothing

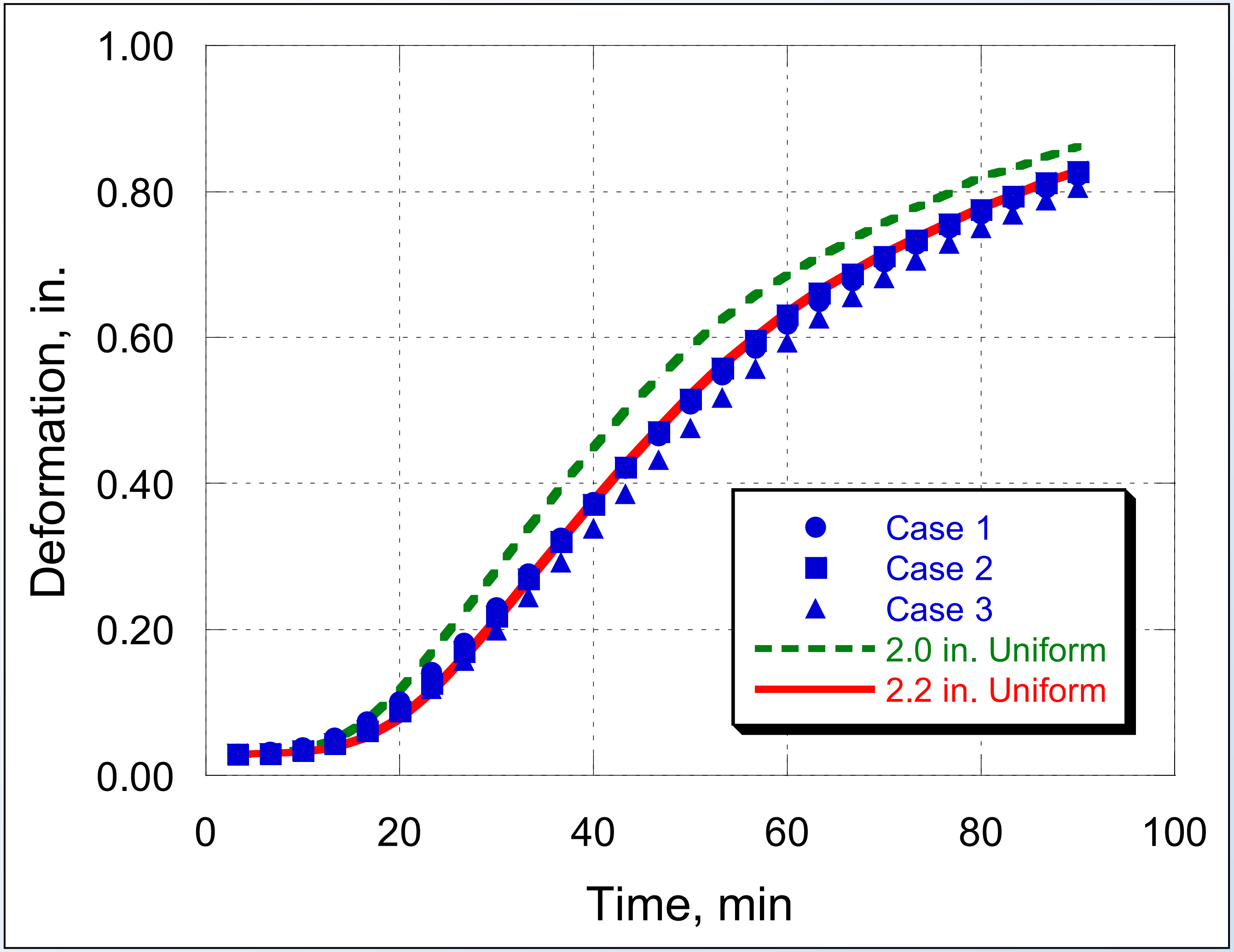
5-point Smoothing



Results for Original SFRM



Results for Upgraded SFRM



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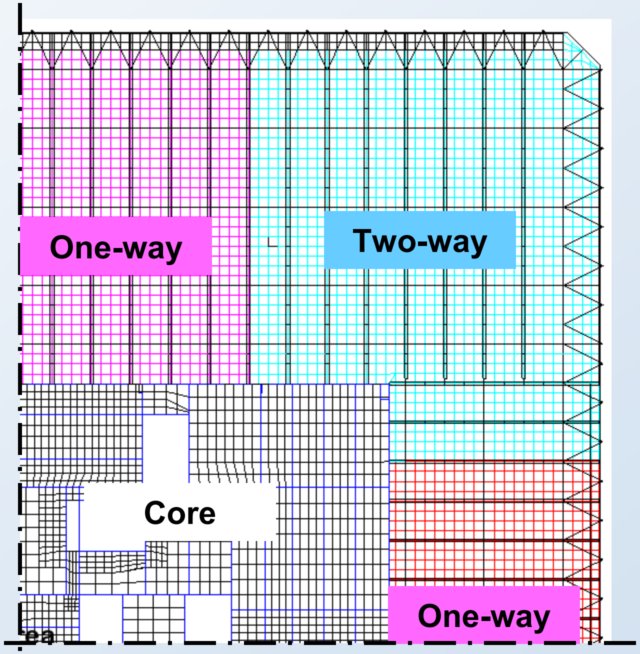
Fireproofing Thickness in Thermal Modeling

- Floor trusses (Original):
  - Main: T = 0.6 in.
  - Bridging (Two-way): T = 0.6 in.
  - Bridging (One-way) and struts: T = 0.3 in.
  - Saddle and damper: T = 0 in.
- Floor trusses (Upgrade):
  - T = 2.2 in., except dampers T = 0 in.
- Other elements: Specified thickness
  - Average tends to exceed specified thickness
  - Variability reduces effectiveness

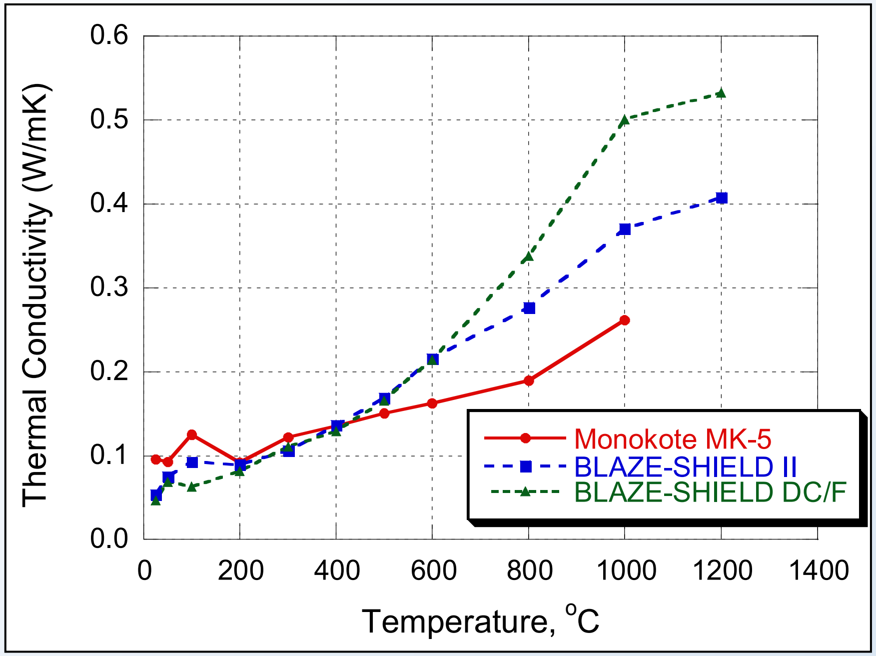


Thermal and Physical Properties of SFRM

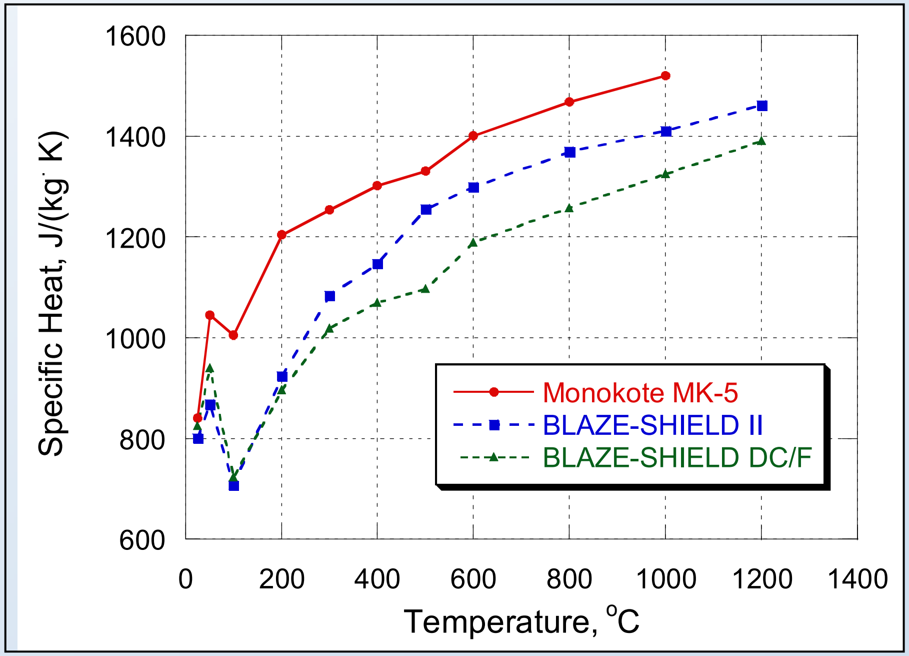
- Materials
  - CAFCO® BLAZESHIELD® Type DC/F (Original)
  - CAFCO® BLAZESHIELD® Type II (Upgrade)
  - Monokote® MK-5® (WTC 7)
- Properties as function of temperature
  - Thermal conductivity
  - Specific heat capacity
  - Density
  - Coefficient of thermal expansion

Example Results

Thermal Conductivity



Specific Heat Capacity



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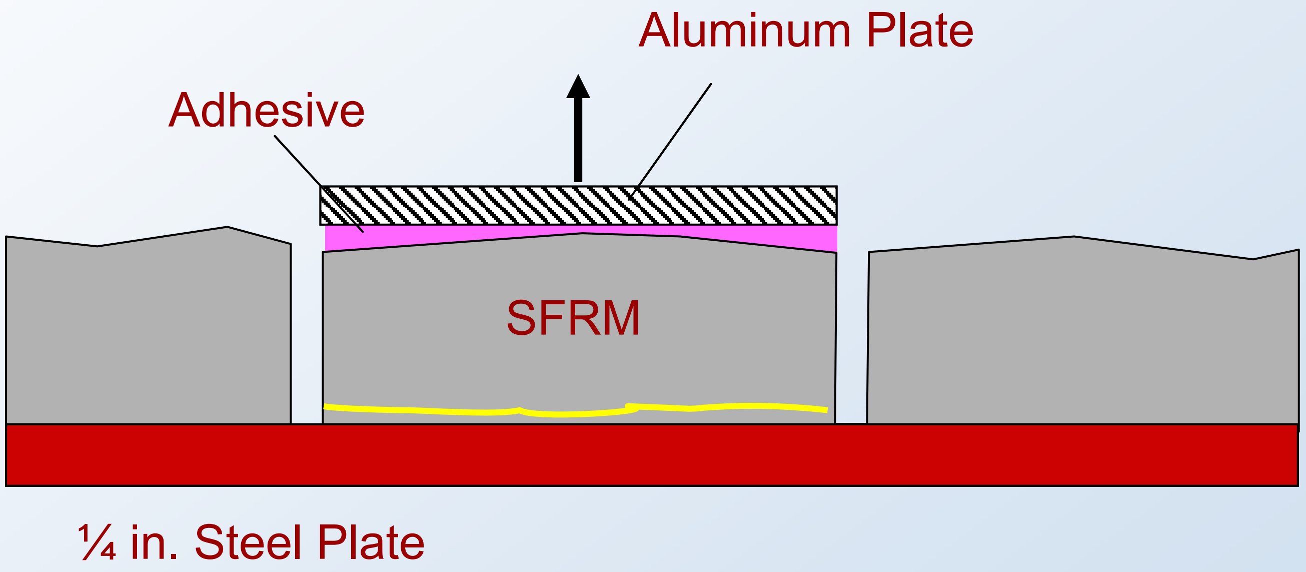
Impact Damage

- SFRM was dislodged
  - Debris field
  - Localized accelerations and deformations
- Estimate extent of dislodged SFRM
  - Measure static adhesive and cohesive tensile strength
  - Develop “failure criteria”
  - Impact analysis and engineering judgment to estimate extent of dislodged SFRM

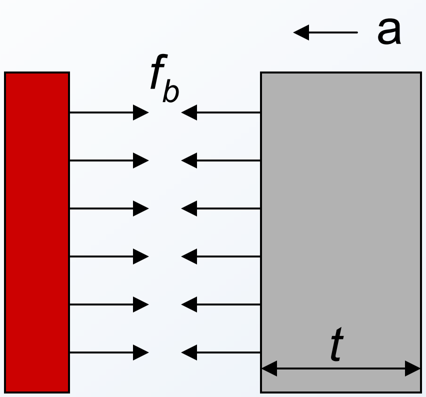
Tensile Pull-off Test




III
IV
V

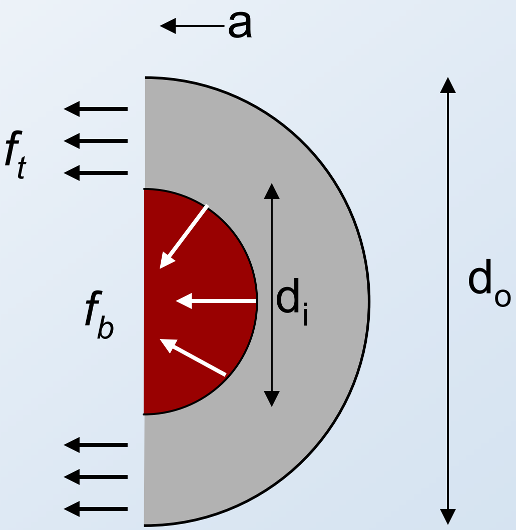
Simple Models

Planar Substrate



$$a = \frac{f_b}{\rho t}$$

Encased Substrate

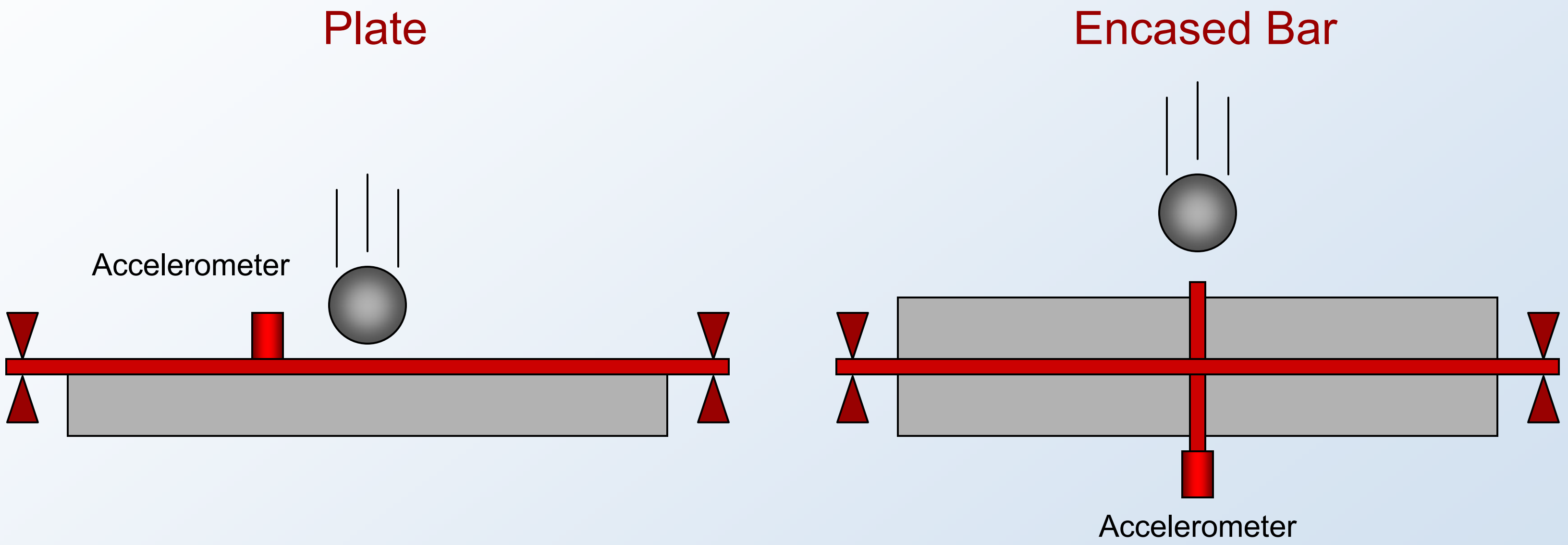


$$\alpha = \frac{f_b}{f_t}$$

$$a = \frac{4 f_t (d_o + (\alpha - 1) d_i}{(d_o^2 - d_i^2)\, \rho\pi}$$

Impact Tests

- Determine acceleration to dislodge SFRM



Summary

- Methodology for assessing condition of SFRM has been reviewed
- Variability of SFRM thickness is taken into account by use of "equivalent thickness"
- Available data used to obtain rational thickness values
    - Floor trusses: original T = 0.6 in.
    - Floor trusses: upgraded T = 2.2 in.
    - Others: Specified thickness
- Temperature dependence of thermal properties established
- Mechanical damage to be estimated on the basis of tests and analysis