SOLUTIONS FOR THE BUILT WORLD

Evaluation of Fire-Exposed Structural Members

Mark Churpek, PE

September 13, 2013
SEAoO Conference

www.wje.com

Wiss, Janney, Elstner Associates, Inc.

Evaluation of Fire-Exposed Structural Members

- Behavior of common structural building materials under exposure to fires
  - During (elevated temperature) and post fire behavior
  - Concrete, CMU, Wood, and Steel
- General and material specific investigative techniques for assessing structures after a fire
  - Field investigations
  - Laboratory studies
  - Equipment
- Determine extent and severity of structural damage
- References for guidance on fire damage investigations

WJE Evaluation of Fire Exposed Structural Members Page 2

All Structures *Safety and Information Gathering*

- Verify structure is safe to enter
  - Excessive deflections?
  - Indications of excessive heat exposure?
- Construction drawings available?
- Shoring necessary?
- Have authorities released site?
- Ask questions about fire:
  - Reported location of origin?
  - Time and duration of fire?
  - Fuel sources?
- Hazardous materials present?

WJE Evaluation of Fire Exposed Structural Members Page 3

All Structures *Condition of Nearby Components*

Vinyl-based paints	Structural steel paint	Melts, flows, bubbles, or burns	250 °F (120 °C)

WJE Evaluation of Fire Exposed Structural Members Page 4

All Structures *Condition of Nearby Components*

WJE Evaluation of Fire Exposed Structural Members Page 5

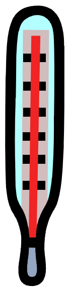
Fire Investigations (Non-Structural) *References*

- *NFPA 921: Guide for Fire and Explosion Investigations*, Quincy, MA: National Fire Protection Association, 2011
- Dehaven, John D., and Icove, David J., *Kirk's Fire Investigation*, Upper Saddle River, NJ: Pearson, 2012

WJE Evaluation of Fire Exposed Structural Members Page 6

Reinforced Concrete Structures
Behavior

What Happens to Concrete During a Fire?



- 2250 ºF: Concrete melts
- 1650 ºF: Cement paste decomposes to powder
- 1000 ºF: Dehydration complete
- 212 ºF: Concrete loses free water, cement paste dehydrates (and shrinks), aggregate undergoes volumetric expansion
- > ambient temperature, all materials begin to expand

WJE Evaluation of Fire Exposed Structural Members Page 7

Reinforced Concrete Structures
Visual Distress

WJE Solutions for the Built World Page 8

Reinforced Concrete Structures
Visual Distress

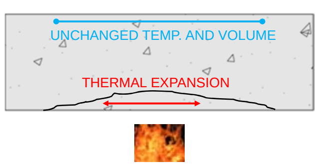
WJE Solutions for the Built World Page 9

Reinforced Concrete Structures
Visual Distress

WJE Evaluation of Fire Exposed Structural Members Page 10

Reinforced Concrete Structures
Distress Mechanisms

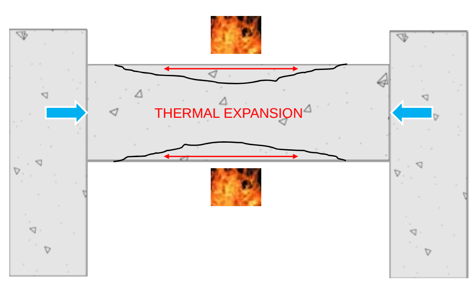
Thermal Differential



WJE Evaluation of Fire Exposed Structural Members Page 11

Reinforced Concrete Structures
Distress Mechanisms

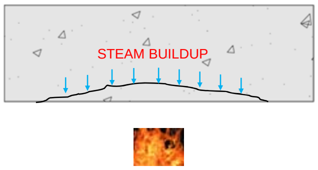
Restrained Expansion



WJE Evaluation of Fire Exposed Structural Members Page 12

Reinforced Concrete Structures
Distress Mechanisms

Internal Pressure Due to Steam



Reinforced Concrete Structures
Distress Mechanisms

Rapid Heating and Cooling – Thermal Shock

Reinforced Concrete Structures
Distress Mechanisms

Varying Thermal Properties

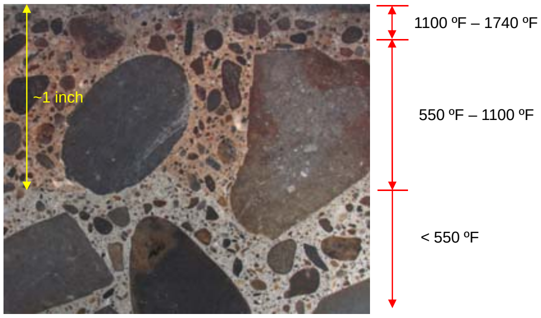
Reinforced Concrete Structures
Distress below the surface?

Reinforced Concrete Structures
Petrographic Examination

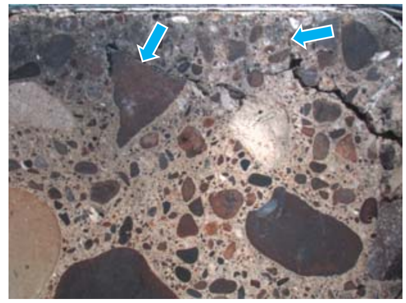
- ASTM C856 Standard Practice for Petrographic Examination of Hardened Concrete
  - Petrology: The science that deals with the mode of occurrence, composition, classification and origin of rocks
  - Petrography: An adjunct to Petrology and Field Geology. Petrography uses laboratory methods to characterize the texture and composition of rock bodies and interpret their history.
  - Concrete Petrography: Used similar methods to characterize the composition and condition of concrete in a structure.

Reinforced Concrete Structures
Petrographic Examination

Reinforced Concrete Structures
Petrographic Examination



Reinforced Concrete Structures
Petrographic Examination



- Cracking
- Paste/ Aggregate separation

Reinforced Concrete Structures
Strength Loss

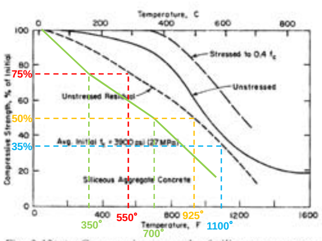


Fig. 2.12(a)—Compressive strength of siliceous aggregate concrete at high temperatures and after cooling.

Factors Affecting Strength:

- Type of aggregate
- Ratio of cement/aggregate
- Air content
- Duration of exposure
- Rate of cooling
- State of stress
- ….

Green Line represents ASTM C856 Estimate of Residual Strength

Reinforced Concrete Structures
Strength Loss

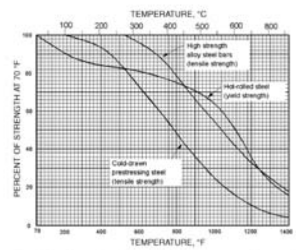
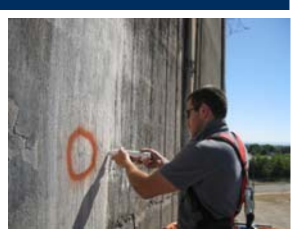


Fig. 2.11—Strength of flexural reinforcement steel bar and strand at high temperatures.

Residual strength unaffected until about 1300 degrees Fahrenheit

Reinforced Concrete Structures
Investigation

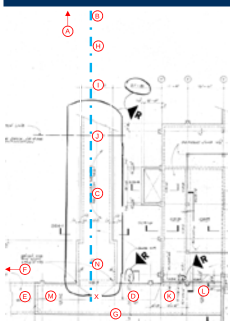
- Field Investigation Tools
  - PPE (hard hat, goggles, respirator, gloves, etc…)?
  - Tape measure, flashlight, notepad, camera, level
  - Field Microscope
  - Hammer/Chain
  - Rebound Hammer
    - Qualitative only

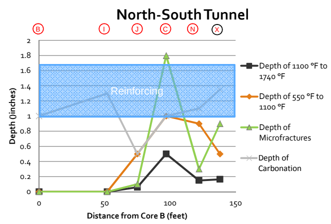


Reinforced Concrete Structures
Investigation

- Cores for petrographic assessment
  - Metal detector to locate reinforcement
  - Mark location and orientation (up/down or inside/outside of cores)
  - Reasonable size (at least 3-4 inch diameter)
  - Takes cores in "control" area, not exposed to significantly elevated temperature
  - Compression tests typically not useful

Reinforced Concrete Structures
Plot of Petrographic Results





WJE Evaluation of Fire Exposed Structural Members Page 25

Reinforced Concrete Structures
Structural Damage?

- Has the residual strength of the concrete been affected?
- Is compression strength important?
  - Does concrete has higher strength than required by design?
- Is the damage at a critical section?
- How close is reinforcing to the surface?
  - Has the concrete to reinforcing bond been disrupted?

WJE Evaluation of Fire Exposed Structural Members Page 26

Reinforced Concrete Structures
References

- *ACI 216.1/TMS-02016: Code Requirements for Determining Fire Resistance of Concrete and Masonry Assemblies*", American Concrete Institute, 2007
- *ASTM 856 Standard Practice for Petrographic Examination of Hardened Concrete*, ASTM International
- Lie, T. T., Rowe, T.J., and Line, T.D., Residual Strength of Fire-Exposed Reinforced Concrete Columns, SP-92 T.Z. Harmathy, ed., American Concrete Institute, 1986
- Erlin, Bernard, and Hime, William, Kuenning, William, *Evaluating Fire Damage to Concrete Structures*, Concrete Construction, Dec. 1972
- Erlin, Bernard, and Hime, William, *The Fire Resistance of Concrete*, Concrete Construction, Dec. 2004
- Gosain, Narendra K., et al, *Evaluation and Repair of Fire Damaged Buildings*, Structure Magazine, Sep. 2008

WJE Evaluation of Fire Exposed Structural Members Page 27

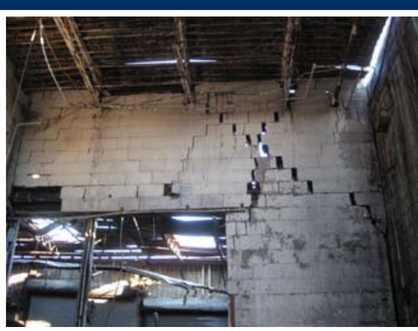
Concrete Masonry Unit (CMU) Structures
CMU versus Concrete

What Happens to CMU During a Fire?

- Similar behavior to concrete (both cementitious materials); however, common differences:
  - CMU typically has more void space
    - Allowance for expansion without disruption of matrix
  - Reinforcement if present often near center of CMU
    - Loss of strength on tension face may have no effect on ultimate capacity; no disruption of bond due to bar being in center of wall
  - Completed masonry wall not homogeneous
    - Masonry units experience different behavior than mortar joints (mortar joints more susceptible to damage)

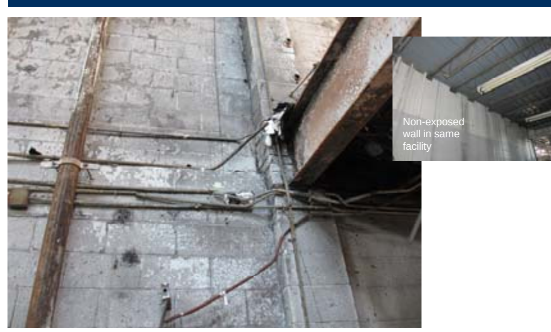
WJE Evaluation of Fire Exposed Structural Members Page 28

CMU Structures
Visual Distress



WJE Evaluation of Fire Exposed Structural Members Page 29

CMU Structures
Visual Distress



WJE Evaluation of Fire Exposed Structural Members Page 30

CMU Structures
Visual Distress

- Soft or friable mortar
- Bond line separations

CMU Structures
Visual Distress

CMU Structures
Investigation

- Field Investigation Tools
  - PPE (hard hat, goggles, respirator, gloves, etc…)?
  - Tape measure, flashlight, notepad, camera, level
  - Field Microscope
  - Hammer/Chain
  - Awl/probe – mortar joints
  - Rebound Hammer
    - Qualitative only
- Cores for petrographic examination

CMU Structures
References

- Many references listed for concrete structures applicable
- *TEK 7-5A, Evaluating Fire Exposed Concrete Masonry Walls*, National Concrete Masonry Association, 2006
- *Assessing the Condition and Repair Alternatives of Fire-Exposed Concrete and Masonry Members*, National Codes and Standards Council, 1994

Steel Structures
Behavior

What Happens to Steel During a Fire?

- Strength and modulus of elasticity decrease with increasing heat.

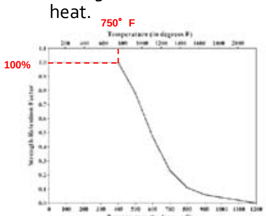


Fig. 2.1. Yield Strength Retention Factors for Structural Steel at Elevated Temperatures

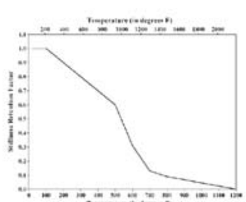


Fig. 2.2. Modulus of Elasticity Retention Factors for Structural Steel at Elevated Temperatures

Steel Structures
Behavior

What Happens to Steel During a Fire?

- The metallurgical properties of hot rolled structural steel members, upon heating and subsequent cooling are generally not deleteriously altered up to 1200 to 1300 ºF
- Many common steel coatings that are not intended for high-temperature applications will blister, burn, or melt between 250 ºF and 600 ºF

Steel Structures
Behavior

Consider the following regarding steel fabrication:

- Steel ingots prior to rolling: 1900 to 2300 °F
- Final rolling for hot-rolled shapes: >1600 °F
- Stress relieving: 1100 to 1200 °F
- Annealing and normalizing: 1500 to 1600 °F

Steel Structures
Behavior

What Happens to Steel During a Fire?

- Strength and modulus of elasticity decrease with increasing heat.

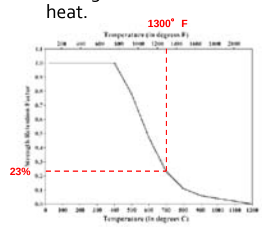


Fig. 2.1. Yield Strength Retention Factors for Structural Steel at Elevated Temperatures

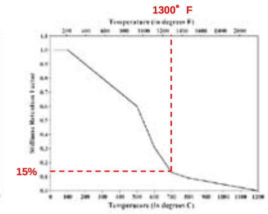
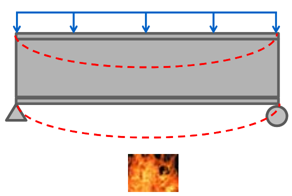


Fig. 2.2. Modulus of Elasticity Retention Factors for Structural Steel at Elevated Temperatures

Steel Structures
Distress Mechanisms

Failure due to reduction in material properties – deflection



Steel Structures
Behavior

What Happens to Steel During a Fire?

- Significant stress development due to restraint

Table 1. Elevated Temperature Effects on Structural Steel

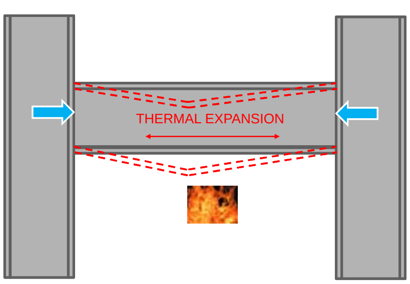
Temp.[a] (°F)	E (× 10³) (ksi)	Therm. Coef. (× 10⁻⁶ in./in./°F)	Restrained Stress (ksi)	Elong. (25 ft.) (in.)	Elong. (40 ft) (in.)
100	29	6.5	5.6	0.06	0.09
200	28	6.5	25	0.26	0.40
300	28	6.7	43[b]	0.46	0.72
400	27	6.9	62[b]	0.66	1.05
600	26	7.2	99[c]	1.08	1.72
800	24	7.6	—	1.52	2.43
1000	20	8.0	—	1.99	3.18
1200	12	8.4	—	2.48	3.97
1400	5	8.8	—	3.00	4.80

[a] Based on an ambient starting temperature of 70 degrees F, an average thermal coefficient was used for each increment. Elongation and stress based on unrestrained and restrained conditions, respectively.
[b] Approximately equal to or exceeds the yield strength of most structural steels.
[c] Exceeds the tensile strength of most structural steels.

$$\sigma = \frac{P}{A} = \frac{\alpha \Delta T E}{L}$$

Steel Structures
Distress Mechanisms

Restrained Expansion - Buckling



Steel Structures
Visual Distress

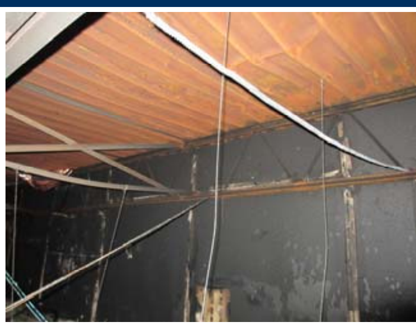
Steel Structures
Visual Distress

WJE Solutions for the Built World Page 43

Steel Structures
Visual Distress

WJE Solutions for the Built World Page 44

Steel Structures
Visual Distress



WJE Solutions for the Built World Page 45

Steel Structures
Investigation

- Field Investigation Tools
  - PPE (hard hat, goggles, respirator, gloves, etc...)?
  - Tape measure, flashlight, notepad, camera,
  - Level, plumb bob, string line, laser level
  - Extraction of coupons typically unnecessary

WJE Solutions for the Built World Page 46

Steel Structures
Investigation

- Suggested Categorization
  - Category I: "Straight" members that appear unaffected.
    - Confirm slight dimensional changes are within fabrication/erection tolerances or if not, if dimensional variations are OK
  - Category II: Member noticeably deformed but could be heat straightened if deemed economical
    - Clearly beyond typical fabrication tolerance, but may be salvaged with straightening or reinforcing
  - Category III: Severely deformed members
    - May have exceeded temperature that alters material properties; however generally a mute point since typically well beyond repair

WJE Solutions for the Built World Page 47

Steel Structures
References

- Tide, R.H.R, *Integrity of Structural Steel After Exposure to Fire*, American Institute of Steel Construction, Engineering Journal, First Quarter, 1998
- Gewain, R., Iwankiw, N., and Alfawakhiri, Farid, *Facts for Steel Buildings: Fire*, American Institute of Steel Construction, 2003

WJE Evaluation of Fire Exposed Structural Members Page 48

Wood Structures
Behavior

What Happens to Wood During a Fire?

- Pyrolysis: decomposition of a material into simpler compounds brought about by heat
- Up to 212 ºF: Residual material properties generally unaffected after reconditioning
  - As low as 150 ºF: Could result in permanent alteration during prolonged exposure – not typical in common structure fire
- 550 ºF: Base layer of char
  - Can occur as low as 400 ºF during prolonged exposure
- Most structure fires – high heat, relatively short duration
  - Basis for information presented

Wood Structures
Behavior

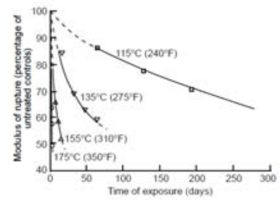


Figure 4–17. Permanent effect of oven heating at four temperatures on modulus of rupture, based on clear pieces of four softwood and two hardwood species. All tests conducted at room temperature.

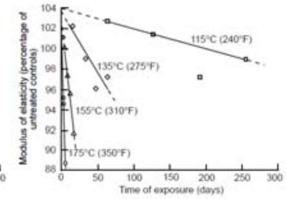


Figure 4–18. Permanent effect of oven heating at four temperatures on modulus of elasticity, based on clear pieces of four softwood and two hardwood species. All tests conducted at room temperature.

Wood Structures
Behavior

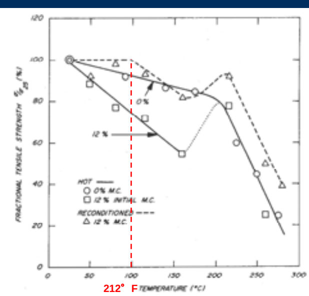


Figure 4.7.—*Fractional tensile strength as function of temperature (Schaffer 1977, 1982b, 1984).*

Wood Structures
Behavior

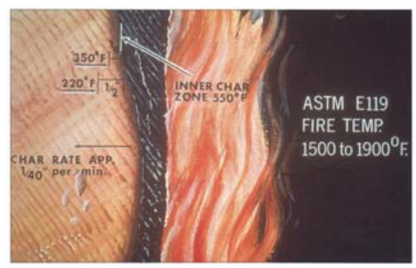


Figure 4.2.—*Illustration of a charring wood member exposed to the standard fire exposure of 815° to 1,038°C.*

Wood Structures
Behavior

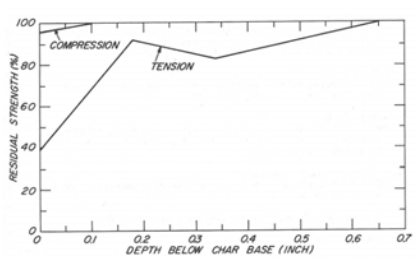
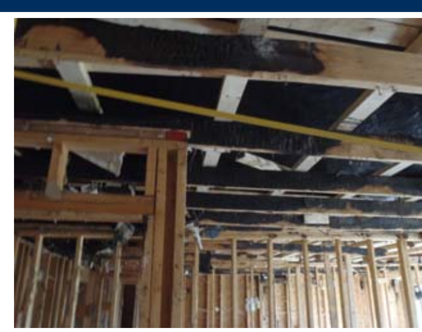


Figure 2.7.4.--Residual strength of fire-exposed and cooled Douglas-fir section as function of depth beyond the char layer (strength at 25° C is 100 pct).

Wood Structures
Visual Distress



Wood Structures
Visual Distress

WJE Evaluation of Fire Exposed Structural Members Page 55

Wood Structures
Visual Distress

WJE Evaluation of Fire Exposed Structural Members Page 56

Wood Structures
Visual Distress

WJE Evaluation of Fire Exposed Structural Members Page 57

Wood Structures
Determining Depth of Char

WJE Evaluation of Fire Exposed Structural Members Page 58

Wood Structures
Investigation

- Field Investigation Tools
  - PPE (hard hat, goggles, respirator, gloves, etc…)?
  - Tape measure, flashlight, notepad, camera,
  - Level, plumb bob, string line, laser level
  - Chisel, calipers
  - Extraction samples to identify species if no stamps visible

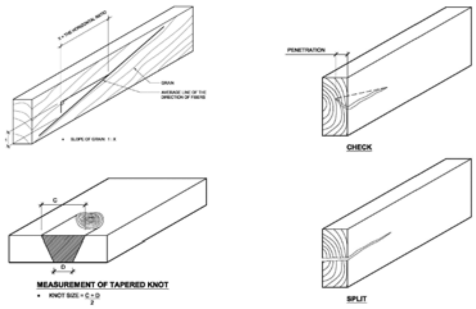
WJE Solutions for the Built World Page 59

Wood Structures
Determination of damage

- Thin members: plywood, OSB, 1x boards
  - If any char, heat affected zone renders significantly damaged
- Most light-framed construction: 2x members
  - If charred, detailed evaluation likely necessary to determine structural significance – however, typically not cost effective
- Heavy timber members: 4x and greater
  - Determine depth of char and heat affected zone
  - Estimate remaining cross-section and strength
  - Consider re-grading

WJE Solutions for the Built World Page 60

Wood Structures
Re-grading



Wood Structures
Post-fire damage due to moisture/exposure

Wood Structures
References

- *Technical Report 10, Calculating the Fire Resistance of Exposed Wood Members*, American Forest & Paper Association, 2003
- Ross, R.J., et al, *Wood and Timber Condition Assessment Manual*, Forest Products Society, 2004
- *Wood Handbook: Wood as an Engineering Material*, United State Department of Agriculture, Forest Products Laboratory, 2010
- *Evaluation, Maintenance and Upgrading of Wood Structures*, American Society of Civil Engineers, 1982
- *Western Lumber Grading Rules*, Western Wood Products Associates, 2004

All Structures
Demolish, Repair, Re-use?

- Questions to answer prior to re-use or repair:
  - May depend on client type (owner vs. insurance company)
    - Pre-existing damage?
  - What temperature did the structural element reach?
    - Which face (tension/compression)?
    - What temperature did the surrounding finishes reach?
  - Is loss of strength likely?
    - Is it significant? Code required demands vs. capacity in current condition?
  - "Significant structural damage" to building per IBC?

All Structures
Summary

- Verify structure is safe to enter; use proper PPE
- Identify needs of client.
  - Extent of damage? Pre-existing?
- Determine type of structure. How is it intended to behave?
- How hot and how long was fire?
- What temperature did structural elements likely reach?
  - What temperature did non-structural elements likely reach?
  - Is this significant? What temperature truly affects the pertinent material properties.
- Determine if structural element is able to be re-used
  - Develop repairs; existing structure code considerations

Questions?

Mark A. Churpek, PE
Wiss, Janney, Elstner Associates, Inc.
mchurpek@wje.com