External Structural Repairs Exposed to Fire: Navigating Building Code Provisions

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Relevance

1. Formal engineering education rarely includes fire science
2. On-the-job experience with fire protection is typically limited to new construction
3. Few designers have fundamental understanding of assumptions behind available data or actual behavior of materials/structure
4. Building codes don’t focus on remedial work
5. Increased use of fiber reinforced polymer (FRP) and other external strengthening methods has led to many questions

Damaging Effects of Fire

- Reduction of strength
- Reduction of stiffness
- Passage of fumes
- Collapse

Typical Fire Damage to Steel Framing

Landmark Fires

Historic:

- Rome, London, and Dresden
- Chicago and San Francisco

Led to development of building codes

Contemporary (in U.S.):

- First Interstate Bank
- Meridian Plaza

Despite long duration neither event led to death or collapse, affirming industry's confidence in ability of codes to protect lives

Heightened Awareness Since 2001

- Three high-rise collapses
- WTC 7 especially troubling
- Undermined confidence in codes

Lessons Learned:

- Dislodging of fireproofing from steel framing
- Effect of thermal expansion on connections
- Inability of UL tests to predict actual performance

Source: NIST (2005) and Carmen Taylor AP, (2001)

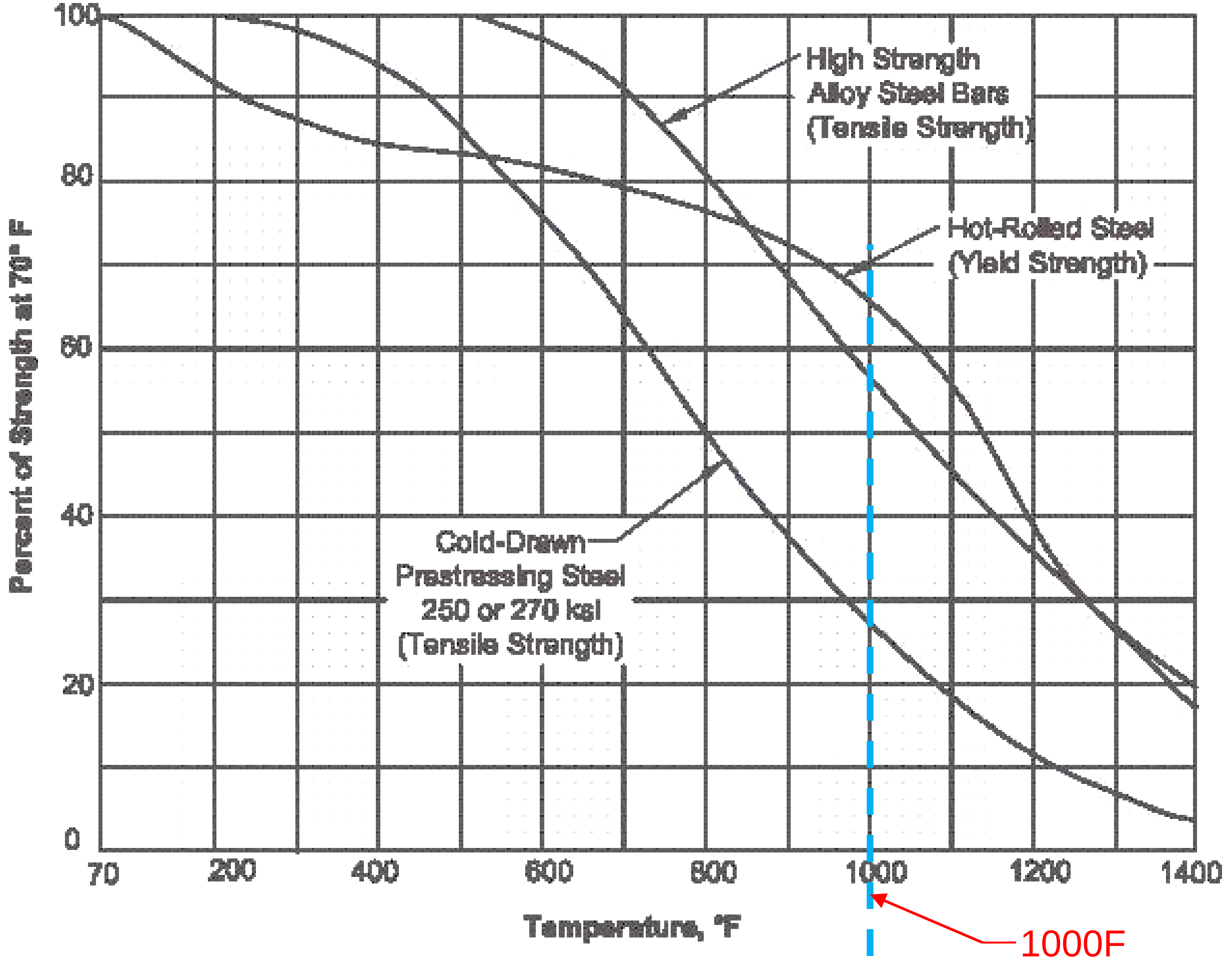
NIST Findings from WTC-related Studies

- Determination of actual fire performance of structural system is currently not the responsibility of any design professional
- Industry practice does not require design professionals to have qualifications necessary to ensure adequate passive fire resistance of structural system
- Architects typically rely on cataloged UL data to specify passive fire resistance needed to comply with building code
- Codes do not treat fire as a structural load case
- Fire protection engineers typically not involved with passive protection

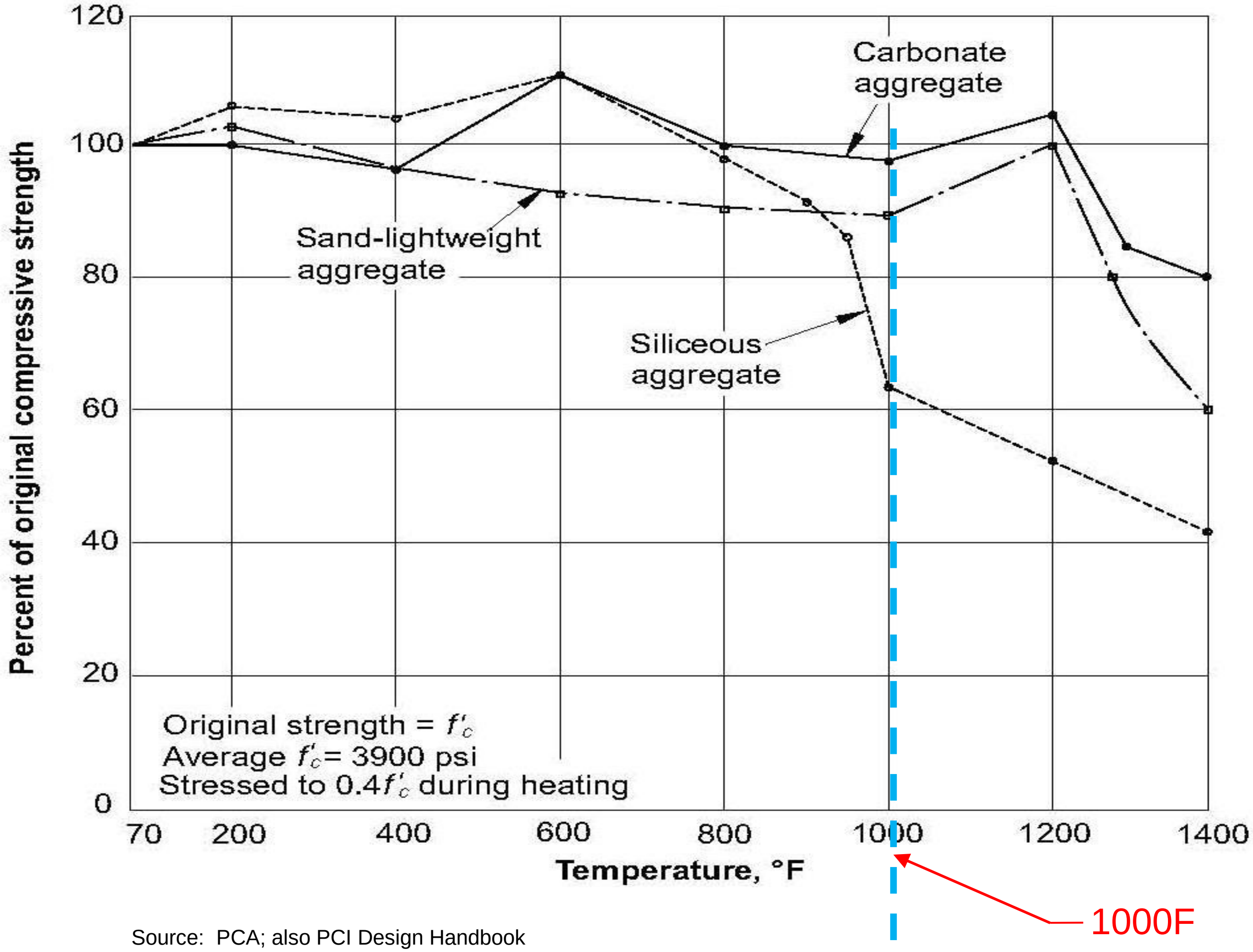
Presentation Objectives

- Describe effect of elevated temperature on structural materials
- Review current approaches in building codes
- Show examples of external structural repairs
- Use case histories to illustrate fire science principles

Effect of Heat on Steel
Strength vs. Temperature



Effect of Heat on Concrete Strength vs. Temperature



Source: PCA; also PCI Design Handbook

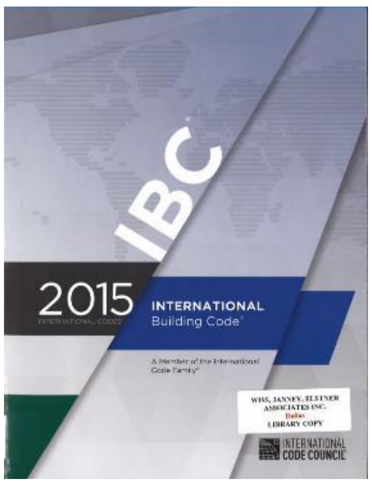
Design Philosophy – Overall

- Objective is life safety
  - Allow time for occupants to evacuate
  - Provide time for first responders
- Code approach does not seek to prevent damage
  - Collapse avoidance is primary structural goal
  - Deflections, cracking, etc. not explicitly considered
- Two fundamental design approaches:
  - **Prescriptive:** historical method in U.S.
  - **Performance:** permitted by building codes

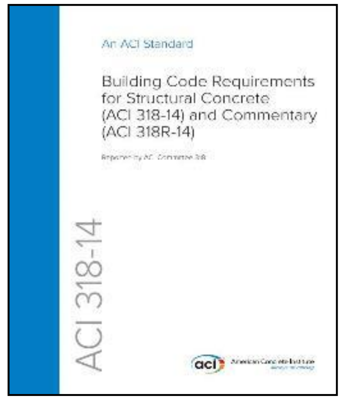
Design Philosophy
Prescriptive vs. Performance

- Prescriptive:
  A) Protective insulation (e.g., cover over rebar)
  B) UL Designs based on ASTM E119 standard fire
  C) Calculations based on ACI 216.1 using ASTM E119
- Performance:
  1. Determine design fire based on credible fuel load
  2. Thermal analysis to determine effect of heat on materials
  3. Structural analysis using reduced material properties and appropriate factor of safety

Building Code Provisions Concrete Construction (New)

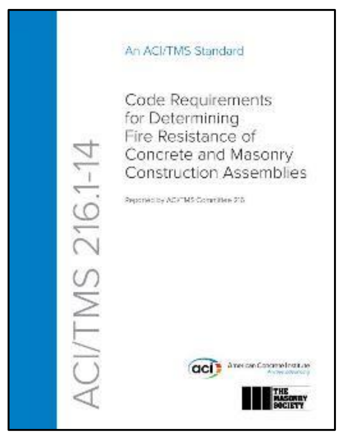


Chap. 19



ACI 318

Chap. 7



ACI 216.1

Room Temperature

4.11—Fire resistance

4.11.1 Structural concrete members shall satisfy the fire protection requirements of the general building code.

4.11.2 Where the general building code requires a thickness of concrete cover for fire protection greater than the concrete cover specified in 20.6.1, such greater thickness shall govern.

Fire Resistance

1.1—Scope

This standard describes acceptable methods for determining the fire resistance of concrete and masonry building assemblies and structural elements, including walls, floor and roof slabs, beams, columns, lintels, and masonry fire protection for structural steel columns. These methods shall be used for design and analysis purposes and shall be based on the fire exposure and applicable end-point criteria of ASTM E119.

IBC Section 703.3
Methods for Determining Fire Resistance

703.3 Methods for determining fire resistance. The application of any of the methods listed in this section shall be based on the fire exposure and acceptance criteria specified in ASTM E 119 or UL 263. The required *fire resistance* of a building element, component or assembly shall be permitted to be established by any of the following methods or procedures:

1. Fire-resistance designs documented in approved sources.
2. Prescriptive designs of fire-resistance-rated building elements, components or assemblies as prescribed in Section 721.
3. Calculations in accordance with Section 722.
4. Engineering analysis based on a comparison of building element, component or assemblies designs having *fire-resistance ratings* as determined by the test procedures set forth in ASTM E 119 or UL 263.
5. Alternative protection methods as allowed by Section 104.11.

ASTM E119
Standard Test Method for Fire Tests …

- Gives requirements for testing components and assemblies
- Defines:
  - Time-temperature curve
  - Furnace characteristics
  - Loading criteria
  - End point criteria
- End points:
  - Failure to sustain load
  - Rise in surface temperature
  - Passage of gas/flames

Designation: E119 – 15

An American National Standard

Standard Test Methods for Fire Tests of Building Construction and Materials[1]

This standard is issued under the fixed designation E119; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the U.S. Department of Defense.

INTRODUCTION

The performance of walls, columns, floors, and other building members under fire-exposure conditions is an item of major importance in securing constructions that are safe, and that are not a menace to neighboring structures or to the public. Recognition of this is registered in the codes of many authorities, municipal and other. It is important to secure balance of the many units in a single building, and of buildings of like character and use in a community; and also to promote uniformity in requirements of various authorities throughout the country. To do this it is necessary that the fire-resistive properties of materials and assemblies be measured and specified according to a common standard expressed in terms that are applicable alike to a wide variety of materials, situations, and conditions of exposure.

Such a standard is found in the test methods that follow. They prescribe a standard exposing fire of controlled extent and severity. Performance is defined as the period of resistance to standard exposure elapsing before the first critical point in behavior is observed. Results are reported in units in which field exposures can be judged and expressed.

The test methods may be cited as the "Standard Fire Tests," and the performance or exposure shall be expressed as "2-h," "6-h," "½-h," etc.

When a factor of safety exceeding that inherent in the test conditions is desired, a proportional increase should be made in the specified time-classification period.

1. Scope*

1.1 The test methods described in this fire-test-response standard are applicable to assemblies of masonry units and to composite assemblies of structural materials for buildings, including loadbearing and other walls and partitions, columns, girders, beams, slabs, and composite slab and beam assemblies for floors and roofs. They are also applicable to other assemblies and structural units that constitute permanent integral parts of a finished building.

1.2 It is the intent that classifications shall register comparative performance to specific fire-test conditions during the period of exposure and shall not be construed as having determined suitability under other conditions or for use after fire exposure.

1.3 *This standard is used to measure and describe the response of materials, products, or assemblies to heat and flame under controlled conditions, but does not by itself incorporate all factors required for fire hazard or fire risk assessment of the materials, products or assemblies under actual fire conditions.*

1.4 These test methods prescribe a standard fire exposure for comparing the test results of building construction assemblies. The results of these tests are one factor in assessing predicted fire performance of building construction and assemblies. Application of these test results to predict the performance of actual building construction requires the evaluation of test conditions.

1.5 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

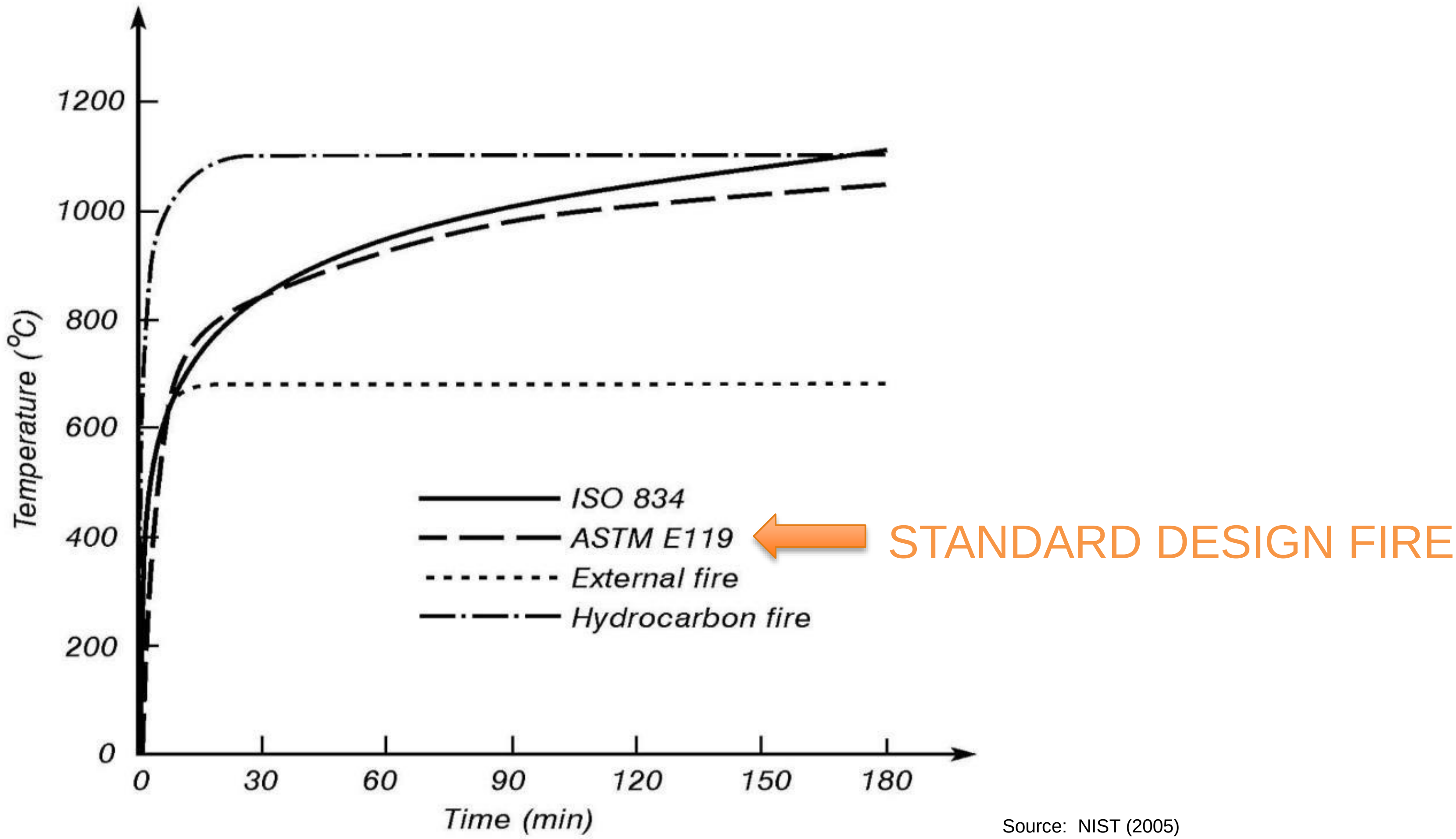
1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the*

[1] These test methods are under the jurisdiction of ASTM Committee E05 on Fire Standards and are the direct responsibility of Subcommittee E05.11 on Fire Resistance.

Current edition approved July 1, 2015. Published September 2015. Originally approved in 1917. Last previous edition approved in 2014 as E119 – 14. DOI: 10.1520/E0119-15.

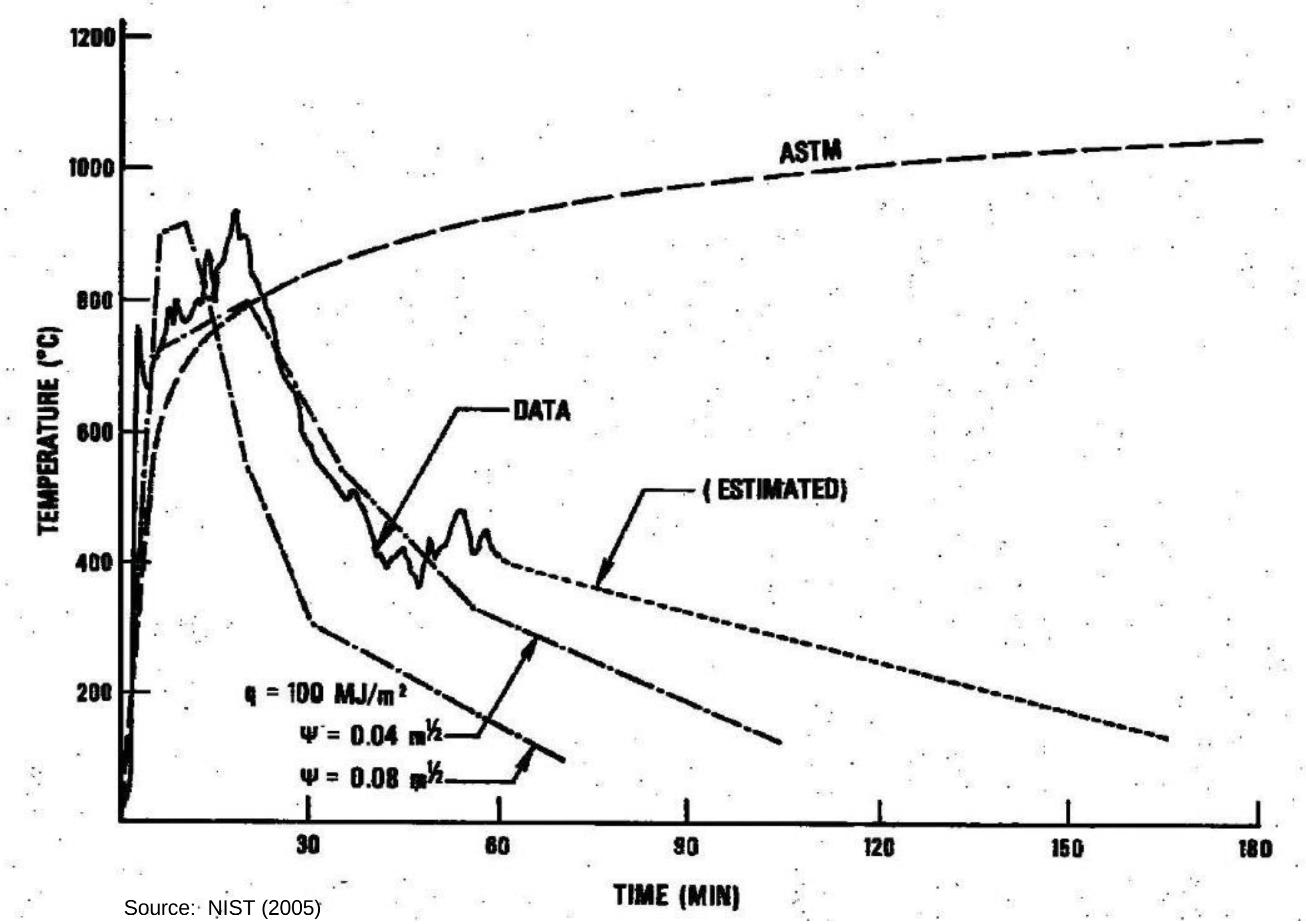
These test methods, of which the present standard represents a revision, were prepared by Sectional Committee on Fire Tests of Materials and Construction, under the joint sponsorship of the National Bureau of Standards, the ANSI Fire Protection Group, and ASTM, functioning under the procedure of the American National Standards Institute.

Time-temperature Curves
ASTM E119 and other criteria



Source: NIST (2005)

Comparison of Standard Design Fire to "Actual" Fires



Source: NIST (2005)

UL Testing
Sample Tech Data for Slab-on-Metal-Deck

- Concrete slab and metal deck assembly tested by manufacturer
- Sample:

FLOOR-CEILING ASSEMBLIES WITH COMPOSITE DECK

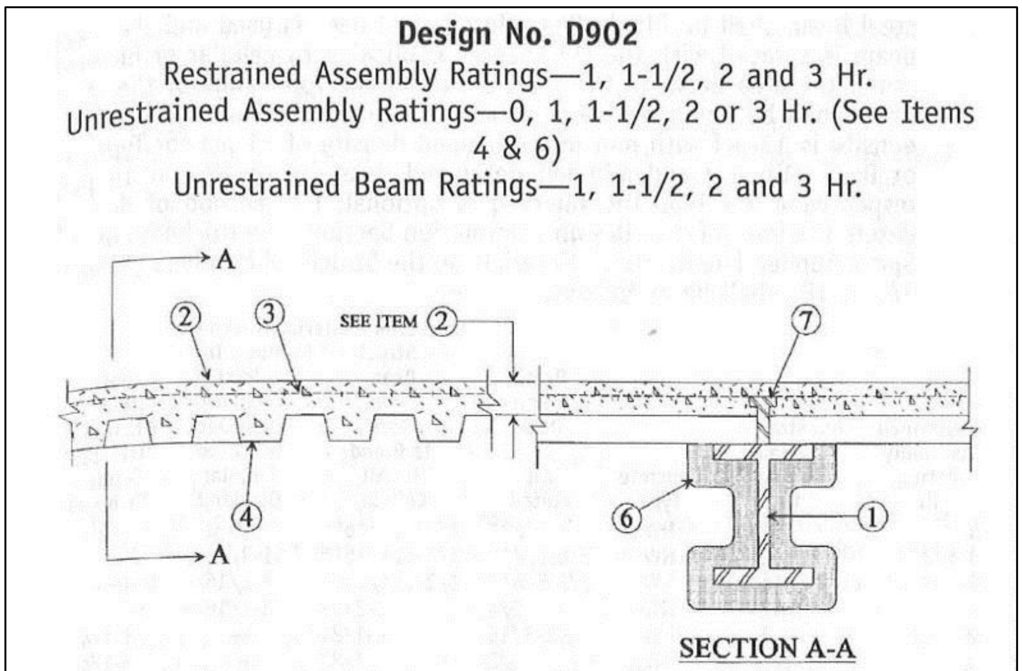
Decks have been tested by Underwriters Laboratories Inc. for their Fire Resistance Ratings. In as much as new listings are continually being added, please contact th design is not listed below. The cellular decks listed comply with U.L. 209 for use as Electrical Raceways.

Restrained Assembly Rating	Type of Protection	Concrete Thickness & Type (1)	U.L. Design No. (2,3,4)	Classified Deck Type	
				Fluted Deck	Cellular Deck (5)
3/4 Hr.	Unprotected Deck	2 1/2" LW	D914 #	1.5VL,1.5VLI,2VLI,3VLI	1.5VLP, 2VLP, 3VLP
			D916 #	1.5VL,1.5VLI,2VLI,3VLI	1.5VLP, 2VLP, 3VLP
1 Hr.	Exposed Grid	2 1/2" NW	D216 +	1.5VL,1.5VLI,2VLI,3VLI	2VLP, 3VLP
	Cementitious	2" NW&LW	D743 *	2VLI,3VLI	2VLP, 3VLP
		2 1/2" NW&LW	D703 *	1.5VLI,2VLI,3VLI	1.5VLP, 2VLP, 3VLP
			D712 *	3VLI	3VLP
			D722 *	2VLI,3VLI	2VLP, 3VLP
			D739 *	1.5VLI,2VLI,3VLI	1.5VLP, 2VLP, 3VLP
			D759	1.5VL,1.5VLI,2VLI,3VLI	1.5VLP, 2VLP, 3VLP
	Sprayed Fiber	2" NW&LW	D859 *	2VLI,3VLI	2VLP, 3VLP
		2 1/2" NW&LW	D832 *	1.5VLI,2VLI,3VLI	1.5VLP, 2VLP, 3VLP
			D847 *	2VLI,3VLI	3VLP
			D858 *	2VLI,3VLI	2VLP, 3VLP
			D871 *	2VLI,3VLI	2VLP, 3VLP
	Unprotected Deck	2 1/2" LW	D902 #	1.5VL,1.5VLI,2VLI,3VLI	1.5VLP, 2VLP, 3VLP
			D914 #	1.5VL,1.5VLI,2VLI,3VLI	1.5VLP, 2VLP, 3VLP
			D916 #	1.5VL,1.5VLI,2VLI,3VLI	1.5VLP, 2VLP, 3VLP
			D918 #	1.5VL,1.5VLI,2VLI,3VLI	1.5VLP, 2VLP, 3VLP
			D919 #	1.5VL,1.5VLI,2VLI,3VLI	1.5VLP, 2VLP, 3VLP
		3 1/2" NW	D902 #	1.5VL,1.5VLI,2VLI,3VLI	1.5VLP, 2VLP, 3VLP
			D916 #	1.5VL,1.5VL [illegible]	[illegible]LP, 2VLP, 3VLP
			D918 #	[illegible]5VL,1.5VL [illegible]	[illegible]LP, 2VLP, 3VLP
			D919 #	1.5VL,1.5VL [illegible]	[illegible]LP, 2VLP, 3VLP

Step 1
Step 2
Step 3
Step 4

UL Design No. D902
Metal Deck

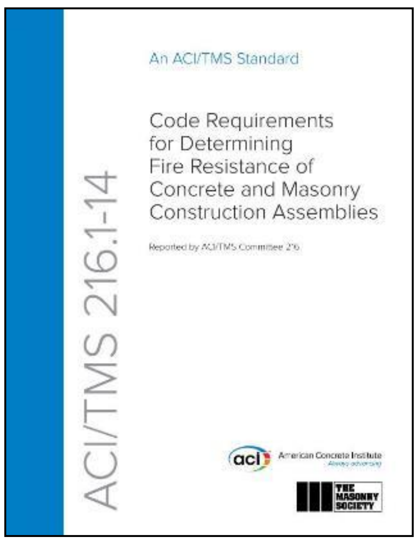
- Details of construction are described in detail in UL Directory
- Designer must incorporate details in drawings or specifications, or make specific reference to UL Design Number



Source: UL Fire Resistance Directory (1999)

ACI 216.1 – Code Requirements for Determining Fire Resistance of Concrete …

Section 4.4
Analytical Methods for Calculating Fire Resistance and Cover Protection



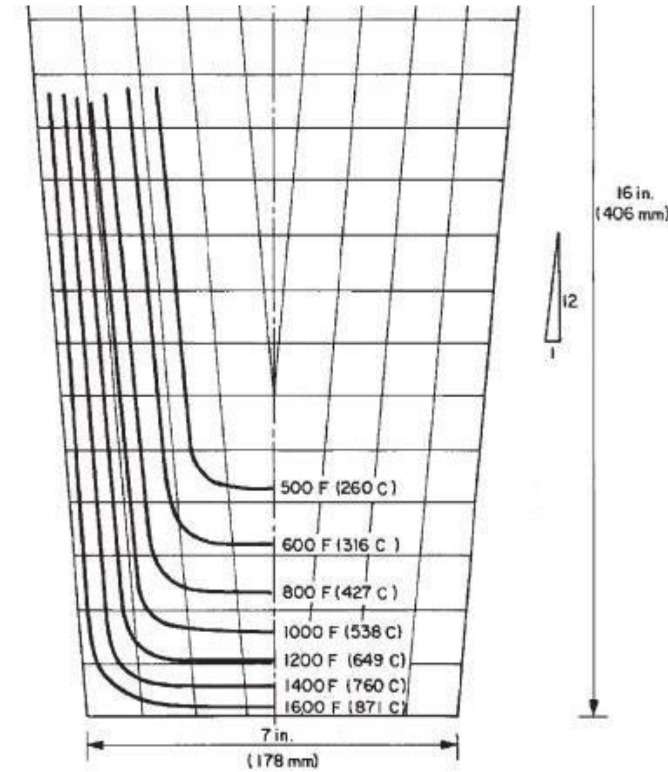


Fig. 4.4.2.3h—Measured temperature distribution at 2 hour fire exposure for semi-lightweight concrete tapered unit.

<u>**Representative Nomogram for DT Stem**</u>

Shortcomings of E119-based Fire Rating System used in U.S.

- ASTM E119 is a comparative test of products under defined fire exposure
- Was not intended to and does not predict actual behavior
- Relies on lab-size test specimens to fit furnace
- Prevailing method of specifying fire protection in the U.S. and is most familiar to manufacturers, designers, and building officials

Load Factors and Strength-reduction Factors

- Building codes (e.g., IBC, ASCE 7, ACI 318, and AISC 360) specify:
  - 1.2 and 1.6 load factors for D and L, respectively
  - <1.0 strength reduction (i.e., *phi*) factors
- Probability of simultaneous occurrence of peak loading considered
- Above factors developed for room temperature
- Probability of simultaneous occurrence of peak gravity loads and a design fire event is extremely low
- Accordingly, ASTM E119 in conjunction with ACI 216.1 define:
  - 1.0 load factors for D and L
  - 1.0 strength reduction (i.e., *phi*) factor

Myths and Misconceptions about UL Ratings and Fireproofing

- Fire rating predicts how long the structure will maintain its integrity in actual fire
- Only UL-listed assemblies are allowed by Code
- Individual components of a UL-listed assembly are rated
- "Fireproofing" means that components will not be damaged

FIRE RESISTANCE RATINGS - ANSI/UL263 (BXUV)—*Continued*

The prefix numbers with an asterisk (*) and the design numbers indicated as "Reserved" in the above table are for future expansion and to cater to new types of systems developed in the future.

II. GENERAL

The following information is appropriate to all fire resistive designs described in this Directory. It is recommended that the users review this information in addition to the general guidelines provided for specific materials and construction types.

Authorities having jurisdiction should be consulted before construction.

Fire resistance ratings apply only to assemblies in their entirety. Except for those separately rated structural members supporting tested assemblies, individual components are not assigned a fire resistance rating and are not intended to be interchanged between assemblies but rather are designated for use in a specific design in order that the ratings of the design may be achieved.

All ratings are based on the assumption that the stability of structural members supporting the assembly are not impaired by the effects of fire. The extent of damage of the test assembly at the rating time is not a criteria for the rating.

Common Reasons for Structural Repairs

- Accommodate increased loading
  - Live load (change in occupancy)
  - Lateral load (wind or seismic)
- Address errors in design or construction
- Remediate deterioration
  - Corrosion
  - Impact/abuse
- Improve serviceability
  - Vibration
  - Deflection

Connection Repairs

- Precast connections
  - Deck members (e.g., double tees, inverted tees, and spandrels
  - Wall panel
  - Column
- Post-installed anchors
  - Original construction
  - Remedial construction
  - Adhesive anchors

Member or System Repairs

- Structural Steel Framing
  - Sub-framing (span shortening or tributary area reduction)
  - Steel plates (cover plates)
- Concrete Framing
  - Member enlargement
  - Steel plates (bonded or bolted)
  - External post-tensioning (EPT)
  - Fiber-reinforced polymer (FRP)

Steel Connection Repairs – Precast DT Bearing Seat

Steel Connection Repairs – Precast DT Flange-to-Flange Connection

Concrete Beam Shear Reinforcing Steel Hanger Rods[1]

[1]Photo shows work-in-progress. Mortar subsequently applied to encase steel.

External Post-Tensioning
1-way Concrete Slab

External Post-Tensioning 2-way Concrete Slab

External Post-Tensioning Precast Double-tee

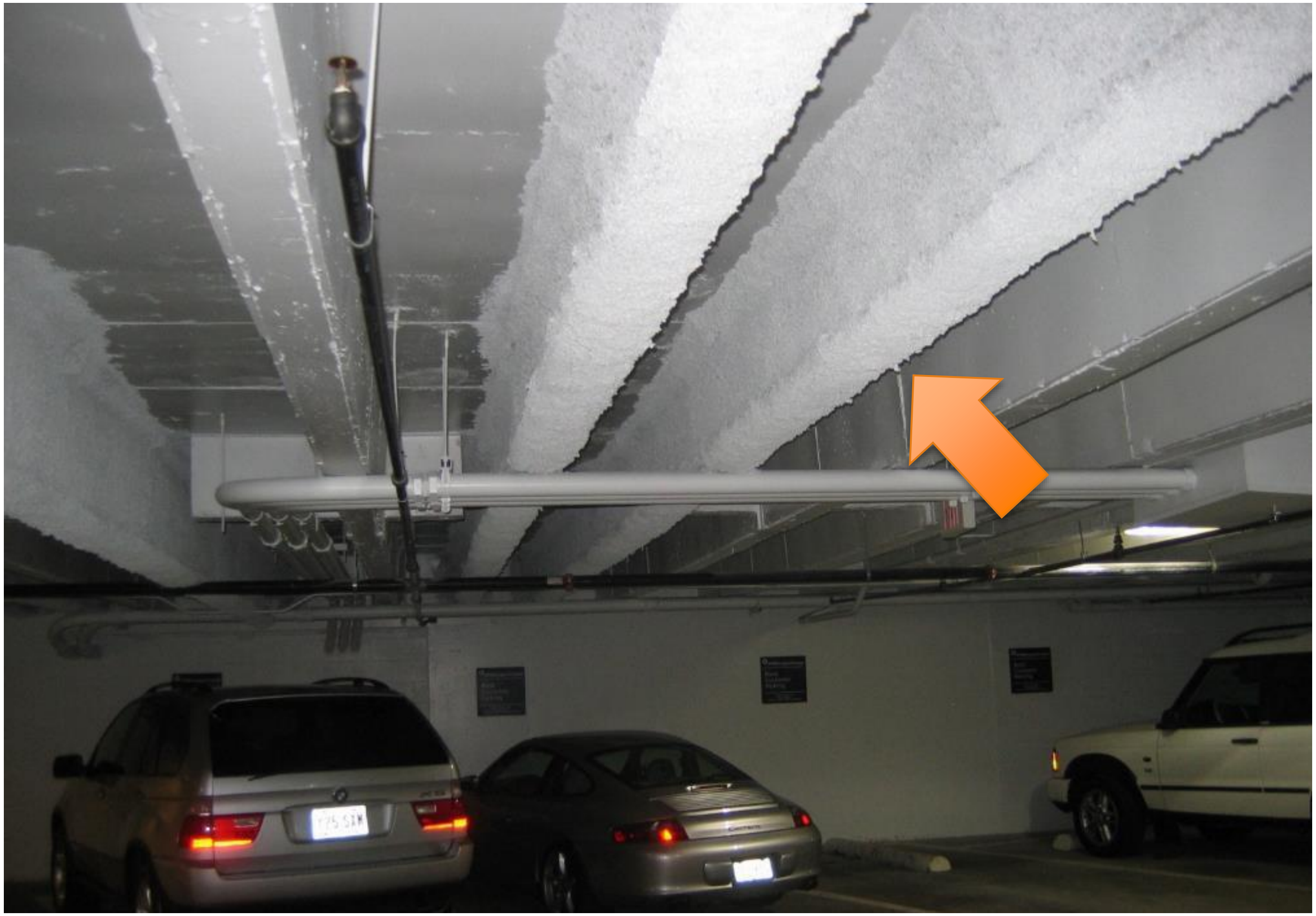
External Post-Tensioning
Precast Raker Beam

Fiber Reinforced Polymer (FRP)

Fiber Reinforced Polymer (FRP)

[1]Photo shows work-in-progress. Fireproofing subsequently applied over FPR.

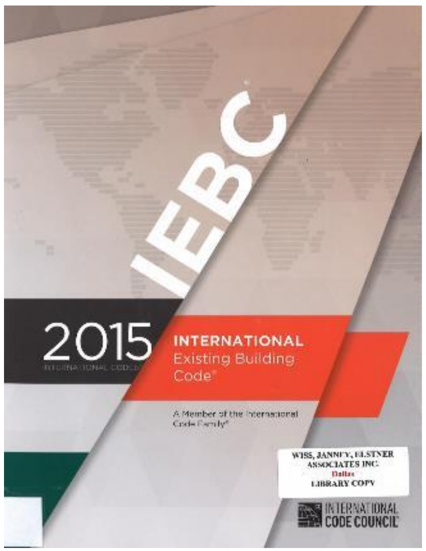
Structural Steel Sub-framing (with SFRM)



Fiber Reinforced Polymer (with SFRM)

Fiber Reinforced Polymer (with SFRM)

Building Code Provisions
Repairs



Sect. 606 → **Room Temperature:**

"New materials to comply with provisions of the IBC"

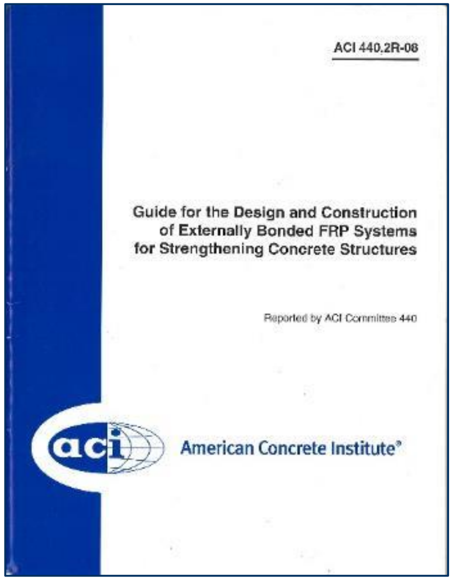
Sect. 603 → **Fire Resistance:**

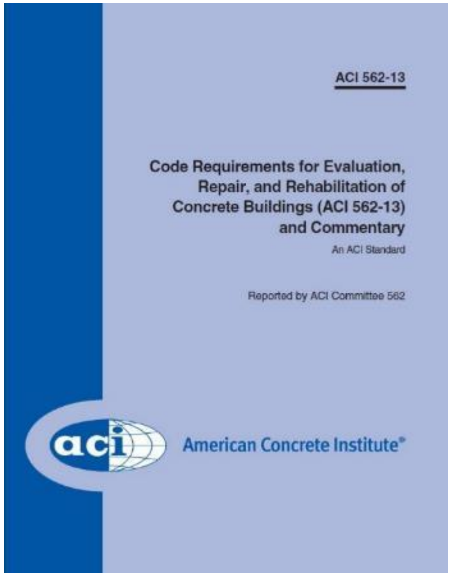
SECTION 603
FIRE PROTECTION

603.1 General. Repairs shall be done in a manner that maintains the level of fire protection provided.

Other Resources for Repairs

- ACI 440.2R-08: Guide to Design of … Externally Bonded FRP ..
- ACI 562-13: Code Requirements for … Repair of Concrete ...

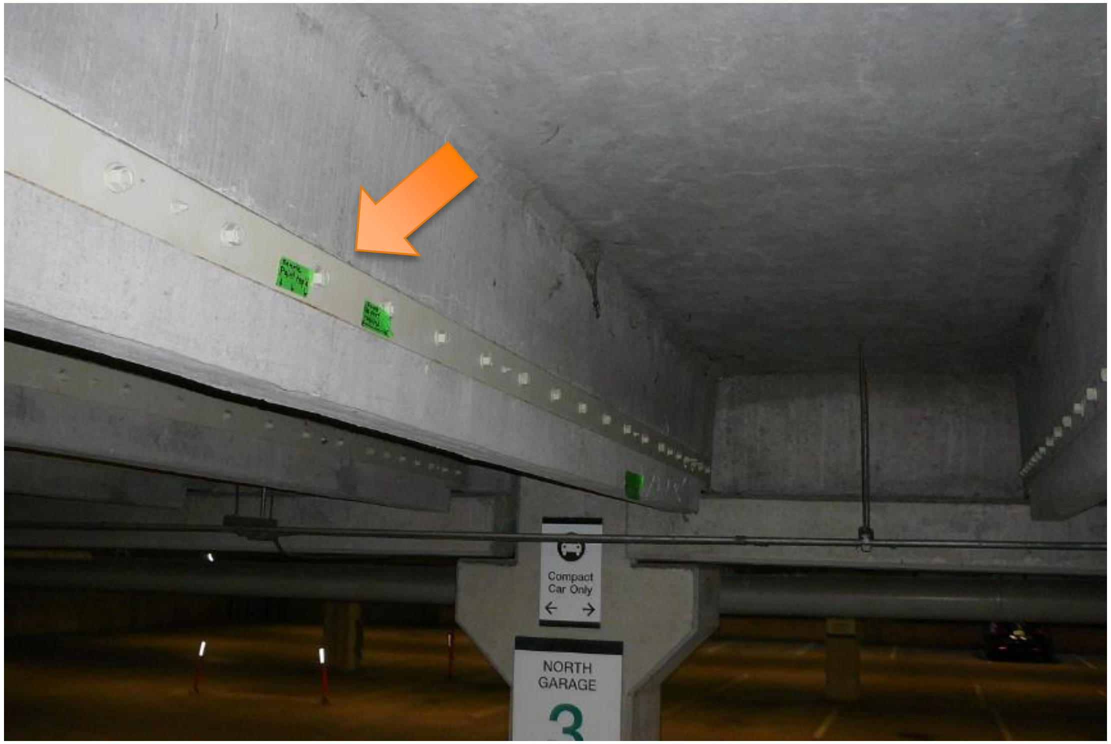




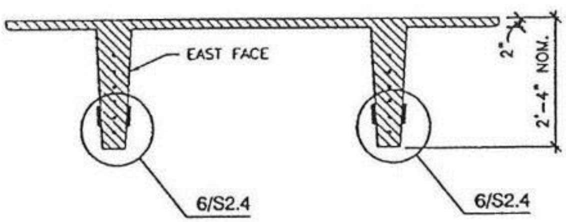
- AISC Fire Facts (Only addresses repair of fire-damaged members)

Case History – Steel Plate Repairs Thermal Analysis to Predict Strength

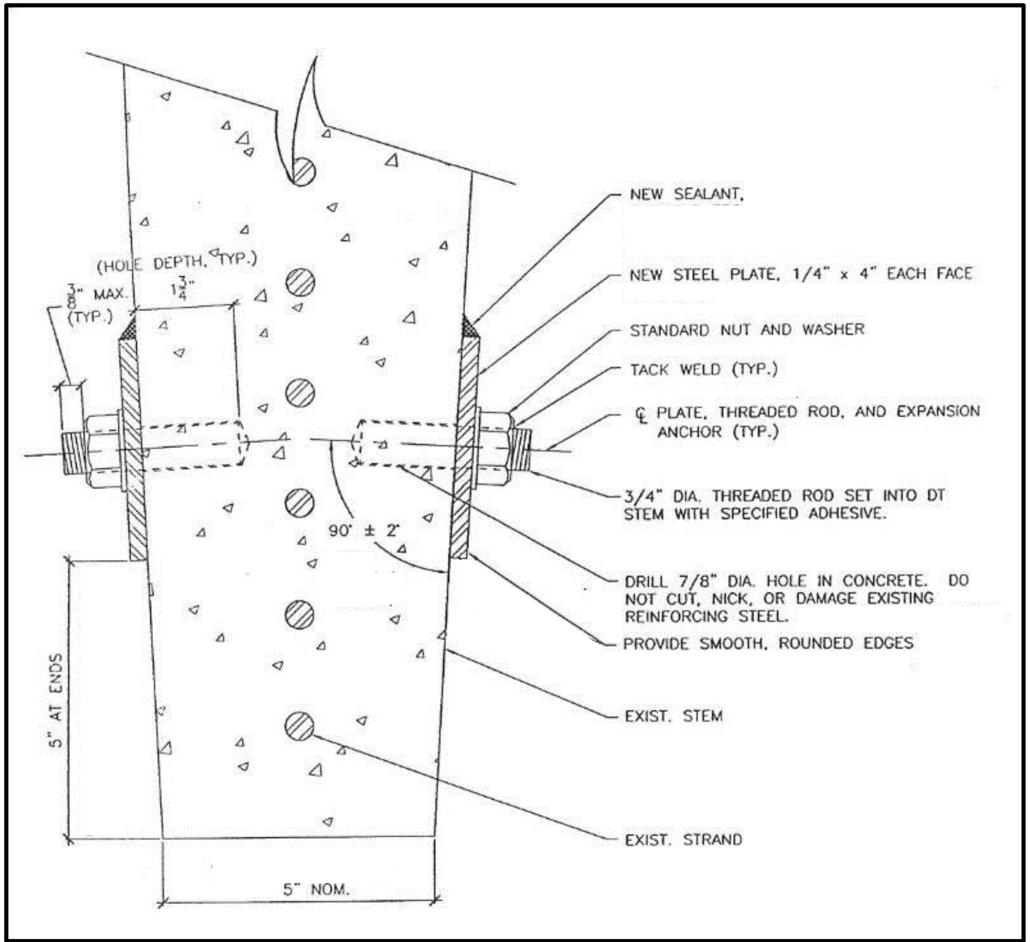
- Precast concrete double tee beam
- Needs flexural strengthening
- Solution: External bolted steel plates
- Question: Do steel plates need to be fireproofed?



Steel Plate Repair
DT Stem Detail



DT Section



Steel Plate Repair
Building Code Criteria for Fire

- Group S-4 Occupancy (UBC 1997)
- Type I Fire-resistive construction
- Table 6-A requires a 2-hour rating

TABLE 6-A—TYPES OF CONSTRUCTION—FIRE-RESISTIVE
For details, see occupancy section in Chapter 3, type of construction sections in t

BUILDING ELEMENT	TYPE I	TYPE II		
	Noncombustible			
	Fire-resistive	Fire-resistive	1-Hr.	N
1. Bearing walls—exterior	4 Sec. 602.3.1	4 Sec. 603.3.1	1	N
2. Bearing walls—interior	3	2	1	N
3. Nonbearing walls—exterior	4 Sec. 602.3.1	4 Sec. 603.3.1	1 Sec. 603.3.1	N
4. Structural frame[1]	3	2	1	N
5. Partitions—permanent	1[2]	1[2]	1[2]	N
6. Shaft enclosures[3]	2	2	1	1
7. Floors and floor-ceilings	2	2	1	N
8. Roofs and roof-ceilings	2 Sec. 602.5	1 Sec. 603.5	1 Sec. 603.5	N

Steel Plate Repair
Methods to Achieve Required Rating

Building Code Provisions

- Section 703 prescribes three methods for showing that required fire-rating has been achieved:
  - Table 7A: Deemed to satisfy ("cover")
  - UL Directory: ASTM E119
  - Calculations: ACI 216.1 and standard fire
- All methods considered acceptable
- None require variance from Building Official

Steel Plate Repair Table 7A Method

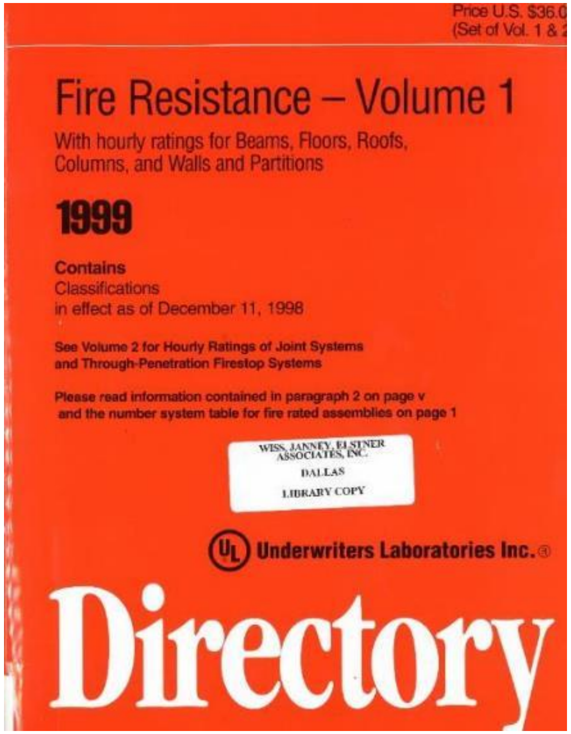
- Covers only conventional structural components
- No guidance for “hybrid” beams or repaired DTs
- No help to designer

TABLE 7-A—MINIMUM PROTECTION OF STRUCTURAL PARTS BASED ON TIME PERIODS FOR VARIOUS NONCOMBUSTIBLE INSULATING MATERIALS[a]—(Continued)

STRUCTURAL PARTS TO BE PROTECTED	ITEM NUMBER	INSULATING MATERIAL USED	MINIMUM THICKNESS OF INSULATING MATERIAL FOR FOLLOWING FIRE-RESISTIVE PERIODS (inches) × 25.4 for mm			
			4 Hr.	3 Hr.	2 Hr.	1 Hr.
1. Steel columns and all members of primary trusses (cont.)	1-7.2	Three layers of 5/8″ (15.9 mm) Type X gypsum wallboard.[3] First and second layer held in place by 1/8″ (3.2 mm) diameter by 1 3/8″ (35 mm) long ring shank nails with 5/16″ (7.9 mm) diameter heads spaced 24″ (610 mm) on center at corners. Middle layer also secured with metal straps at mid-height and 18″ (457 mm) from each end, and by metal corner bead at each corner held by the metal straps. Third layer attached to corner bead with 1″ (25 mm) long gypsum wallboard screws spaced 12″ (305 mm) on center.			1 7/8	
	1-7.3	Three layers of 5/8″ (15.9 mm) Type X gypsum wallboard,[3] each layer screw attached to 1 5/8″ (41 mm) steel studs 0.018 inch thick (0.46 mm) (No. 25 carbon sheet steel gage) at each corner of column. Middle layer also secured with 0.049 inch (0.12 mm) (No. 18 B.W. gage) double strand steel wire ties, 24″ (610 mm) on center. Screws are No. 6 by 1″ (25 mm) spaced 24″ (610 mm) on center for inner layer, No. 6 by 1 5/8″ (41 mm) spaced 12″ (305 mm) on center for middle layer and No. 8 by 2 1/4″ (57 mm) spaced 12″ (305 mm) on center for outer layer.		1 7/8		
	1-8.1	Wood-fibered gypsum plaster mixed 1:1 by weight gypsum to sand aggregate applied over metal lath. Lath lapped 1″ (25 mm) and tied 6″ (152 mm) on center at all ends, edges and spacers with 0.049 inch (0.12 mm) (No. 18 B.W. gage) steel tie wires. Lath applied over 1/2″ (12.7 mm) spacers made of 3/4″ (19 mm) furring channel with 2″ (51 mm) legs bent around each corner. Spacers located 1″ (25 mm) from top and bottom of member and a maximum of 40″ (1016 mm) on center and wire tied with a single strand of 0.049 inch (0.12 mm) (No. 18 B.W. gage) steel tie wires. Corner bead tied to the lath at 6″ (152 mm) on center along each corner to provide plaster thickness.			1 5/8	
2. Webs or flanges of steel beams and girders	2-1.1	Carbonate, lightweight and sand-lightweight aggregate concrete (not including sandstone, granite and siliceous gravel) with 3″ (76 mm) or finer metal mesh placed 1″ (25 mm) from the finished surface anchored to the top flange and providing not less than 0.025 square inch of steel area per foot (53 mm^2 of steel area per meter) in each direction.	2	1 1/2	1	1
	2-1.2	Siliceous aggregate concrete and concrete excluded in Item 2-1.1 with 3″ (76 mm) or finer metal mesh placed 1″ (25 mm) from the finished surface anchored to the top flange and providing not less than 0.025 square inch of steel area per foot (53 mm^2 of steel area per meter) in each direction.	2 1/2	2	1 1/2	1
	2-2.1	Cement plaster on metal lath attached to 3/4″ (19 mm) cold-rolled channels with 0.049 inch (1.24 mm) (No. 18 B.W. gage) wire ties spaced 3″ to 6″ (76 mm to 152 mm) on center. Plaster mixed 1:2 1/2 by volume, cement to sand.			2 1/2[2]	7/8
	2-3.1	Vermiculite gypsum plaster on a metal lath cage, wire tied to 0.165 inch (4.19 mm) diameter (No. 8 B.W. gage) steel wire hangers wrapped around beam and spaced 16″ (406 mm) on center. Metal lath ties spaced approximately 5″ (127 mm) on center at cage sides and bottom.		7/8		
	2-4.1	Two layers of 5/8″ (15.9 mm) Type X gypsum wallboard[3] are attached to U-shaped brackets spaced 24″ (610 mm) on center. 0.018 inch (0.46 mm) (No. 25 carbon sheet steel gage) 1 5/8″ deep by 1″ (41 mm deep by 25 mm) galvanized steel runner channels are first installed parallel to and on each side of the top beam flange to provide a 1/2″ (12.7 mm) clearance to the flange. The channel runners are attached to steel deck or concrete floor construction with approved fasteners spaced 12″ (305 mm) on center. U-shaped brackets are formed from members identical to the channel runners. At the bent portion of the U-shaped bracket, the flanges of the channel are cut out so that 1 5/8″ (41 mm) deep corner channels can be inserted without attachment parallel to each side of the lower flange. As an alternate, 0.021 inch (0.41 mm) (No. 24 carbon sheet steel gage) 1″ by 2″ (25 mm by 51 mm) runner and corner angles may be used in lieu of channels, and the web cutouts in the U-shaped brackets may be omitted. Each angle is attached to the bracket with 1/2″ (12.7 mm) long No. 8 self-drilling screws. The vertical legs of the U-shaped bracket are attached to the runners with one 1/2″ (12.7 mm) long No. 8 self-drilling screw. The completed steel framing provides a 2 1/8″ and 1 1/2″ (54 mm and 38 mm) space between the inner layer of wallboard and the sides and bottom of the steel beam, respectively. The inner layer of wallboard is attached to the top runners and bottom corner channels or corner angles with 1 1/4″ (52 mm) long No. 6 self-drilling screws spaced 16″ (406 mm) on center. The outer layer of wallboard is applied with 1 3/4″ (44.5 mm) long No. 6 self-drilling screws spaced 8″ (203 mm) on center. The bottom corners are reinforced with metal corner beads.			1 1/4	

Steel Plate Repair
UL Directory Method

- Covers DTs and wide flange beams, but not DTs repaired with steel plates
- Might give basis for SFRM
- Requires interpretation and judgment
- Limited help to designer

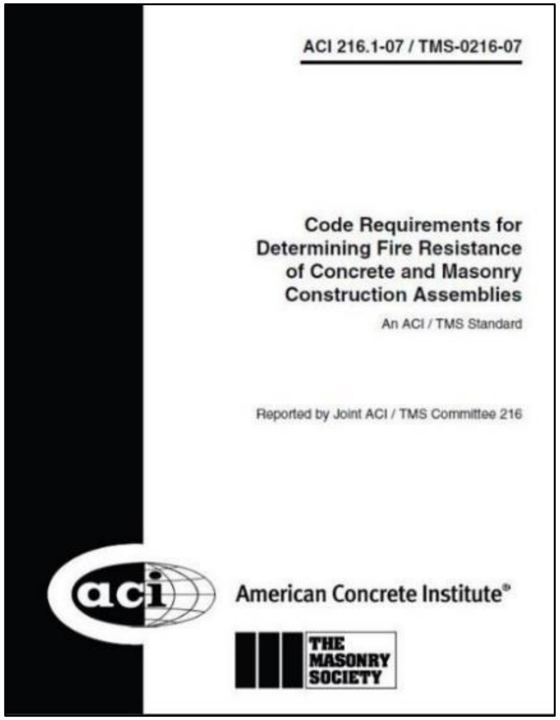


Steel Plate Repair Calculation Method

- Allows use of ACI 216.1 to evaluate strength of member
- ACI 216.1 based on ASTM E119 design curve:

1.1—Scope

This standard describes acceptable methods for determining the fire resistance of concrete and masonry building assemblies and structural elements, including walls, floor and roof slabs, beams, columns, lintels, and masonry fire protection for structural steel columns. These methods shall be used for design and analysis purposes and shall be based on the fire exposure and applicable end-point criteria of ASTM E119.


ACI 216.1-07 / TMS-0216-07

Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies

An ACI / TMS Standard

Reported by Joint ACI / TMS Committee 216

American Concrete Institute®

THE MASONRY SOCIETY

- Building code permits alternative design curves

Building Code Alternative Method
3-step Performance-based Approach

- Step 1: Fire Hazard Analysis, to identify maximum credible fire and develop a design time-temperature curve
- Step 2: Thermal Analysis, to calculate temperature of rebar and concrete during exposure to the fire using finite element based heat transfer principles
- Step 3: Structural Analysis, to see if heated member has sufficient strength when exposed to the fire

Performance-based Approach
Hazard and Thermal Analysis Model

- 20-ft long delivery vehicle
- Six 17” diam. tires, 100 gals fuel
- Rapid rise to peak temperature
- Fire duration of 15 minutes
- FEA-based heat transfer study

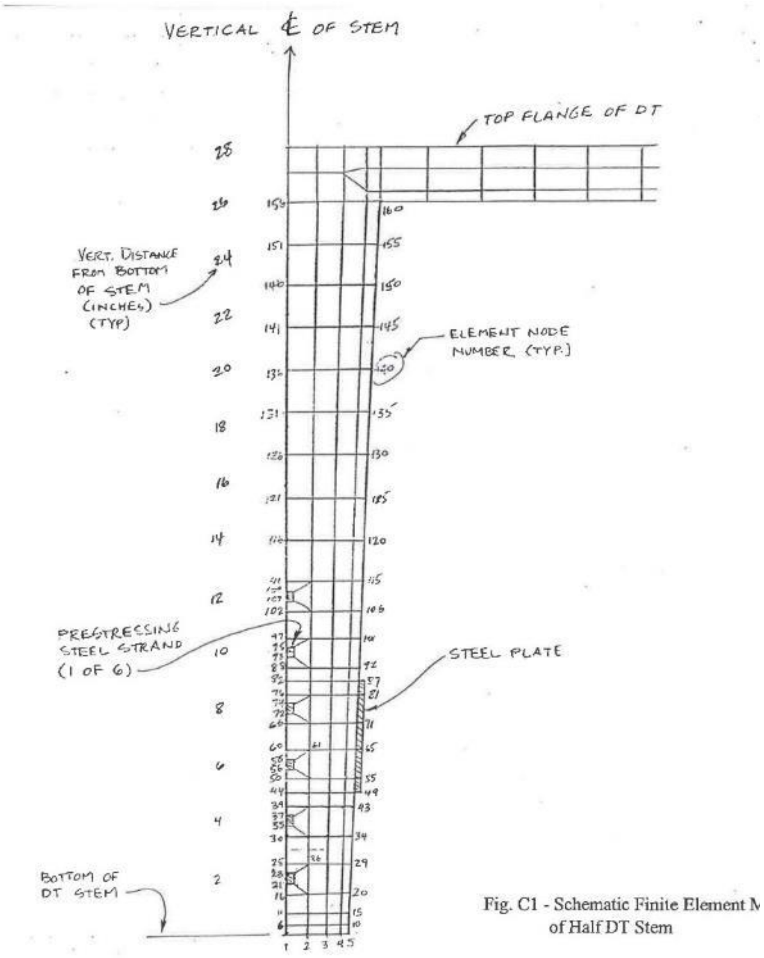
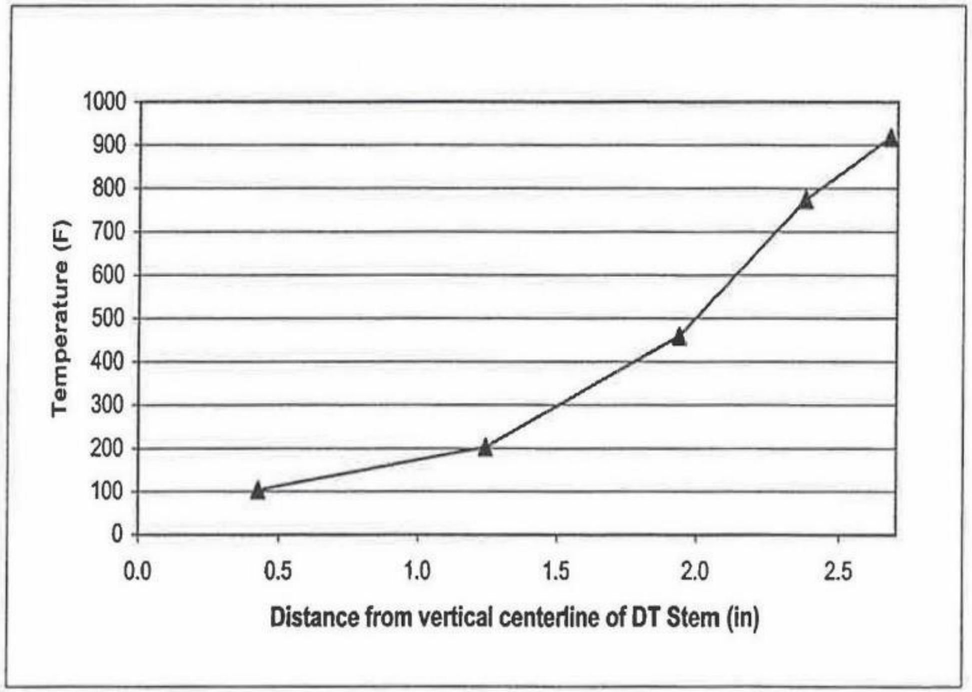
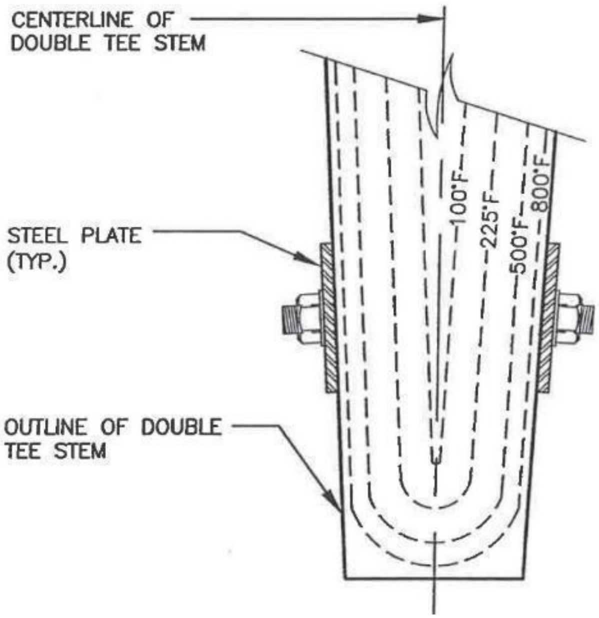


Fig. C1 - Schematic Finite Element M
of Half DT Stem

Performance-based Approach
Results of Thermal Analysis Model

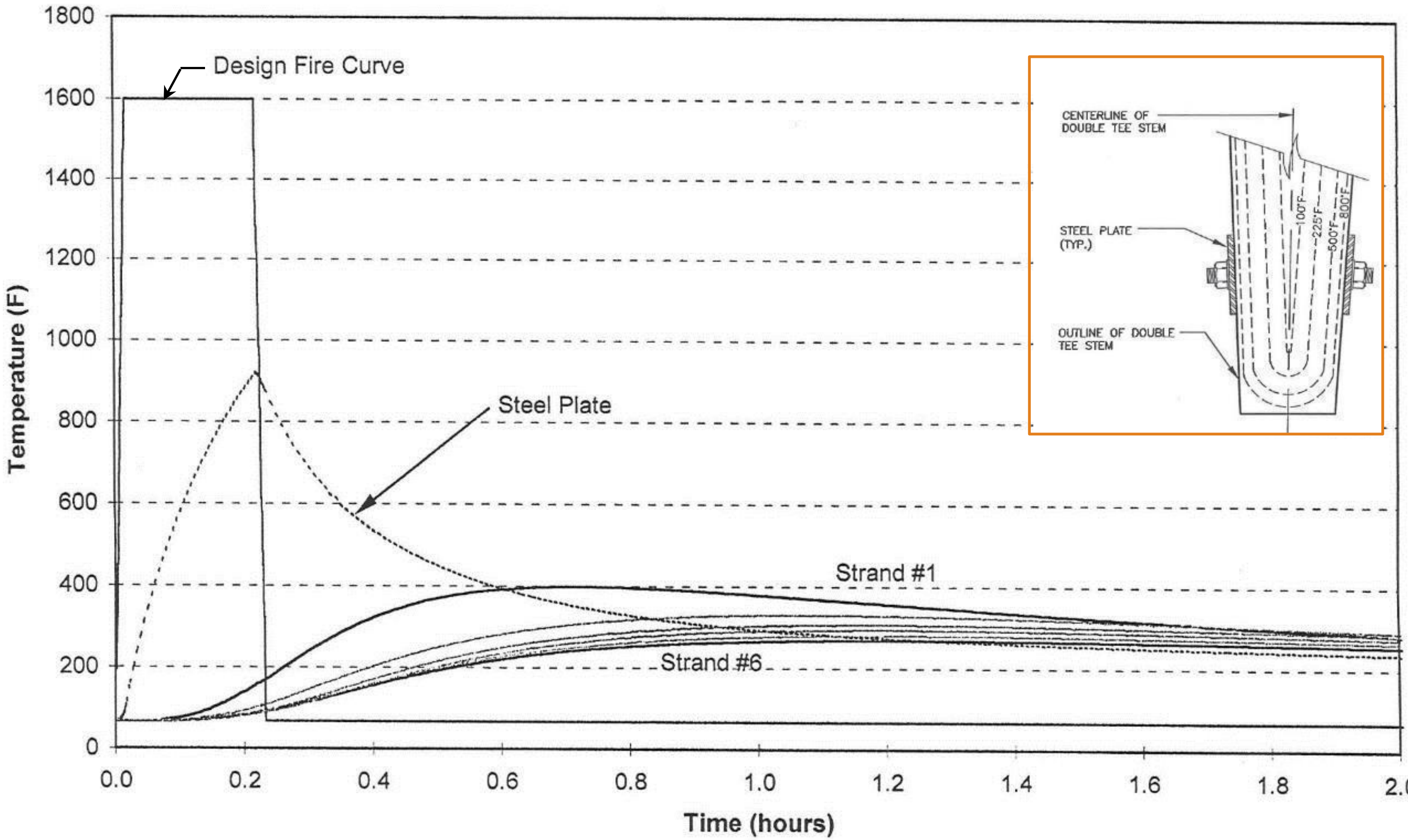


b) Temperature Gradient after 0.23 hours of Exposure to Design Fire

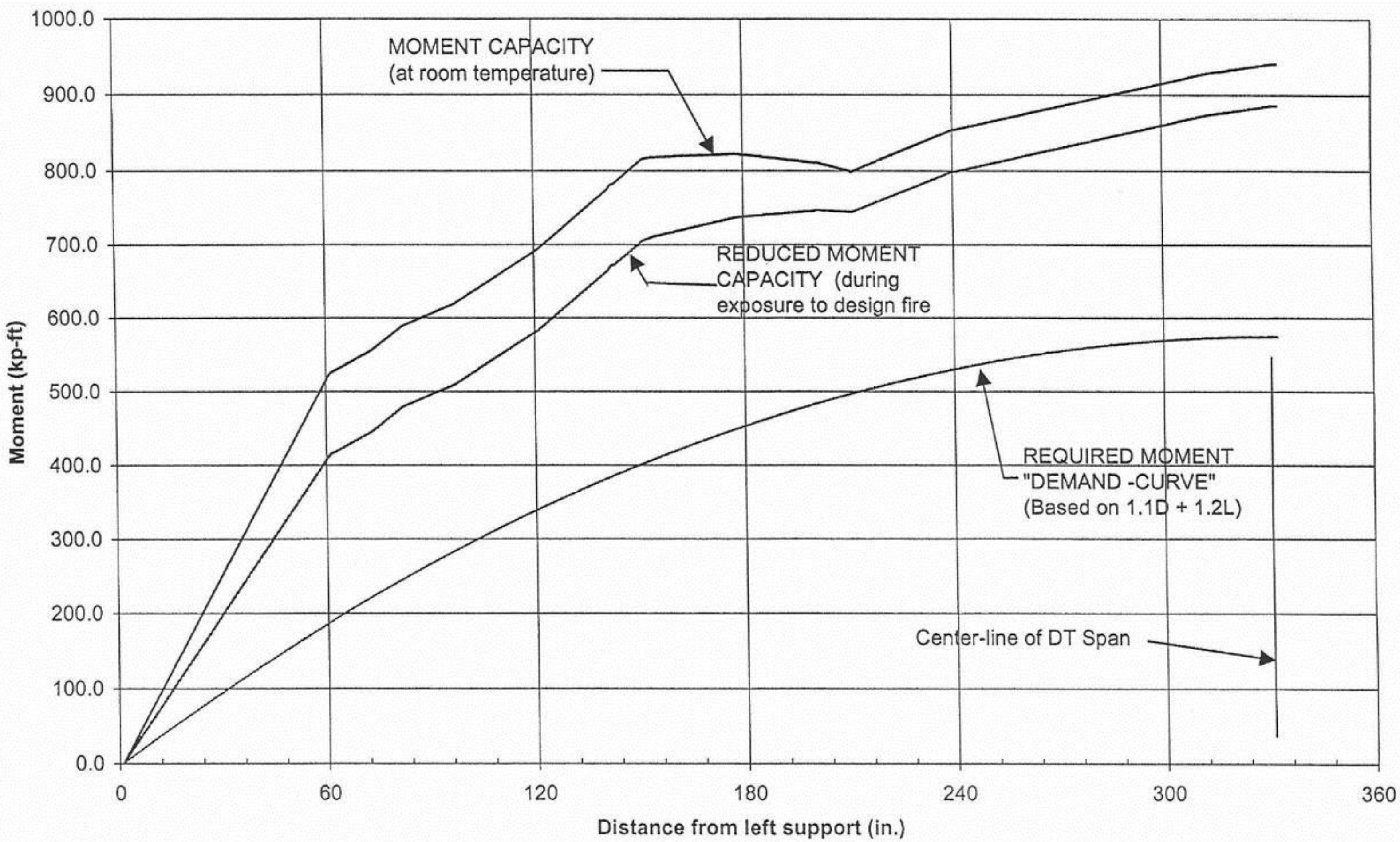


Isotherms after 0.22 hrs of Exposure to Design Fire

Performance-based Approach
Temperature v. Time (FEA results)



Performance-based Approach
Structural Analysis



Steel Plate Repair Summary

- 2-hour rating required using conventional prescriptive method
- Performance-based method approved by Building Official
- Safety demonstrated by FEA-based thermal/structural analysis
- Steel not fireproofed

Performance of FRP When Exposed to Fire

Possible Sources of Information:

- Consensus Industry Documents
  - ACI 440.2R-08: Guide to Design… of Externally Bonded FRP …
  - ACI 562-13: Code Requirements for … Repair of Concrete ...
- Academic Research
  - Industry sponsored
- FRP Manufacturers
  - Technical representatives
  - Product Data Sheet
  - UL test reports

FRP Development Timeline

- Early 1980s: Technology developed in Europe and Japan
- Early 1990s: Introduced to U.S.
- Early-mid 90s: Design guides developed by manufacturers
- Mid 1990s: First large-scale applications in U.S.
- 2002: Publication of ACI 440.2R-02
- 2008: Publication of ACI 440.2R-08

- UL fire testing
  - Mid 1990s: First UL test (column/wall specimens)
  - 2000s - early 2010s: UL tests (beam/slab assemblies)

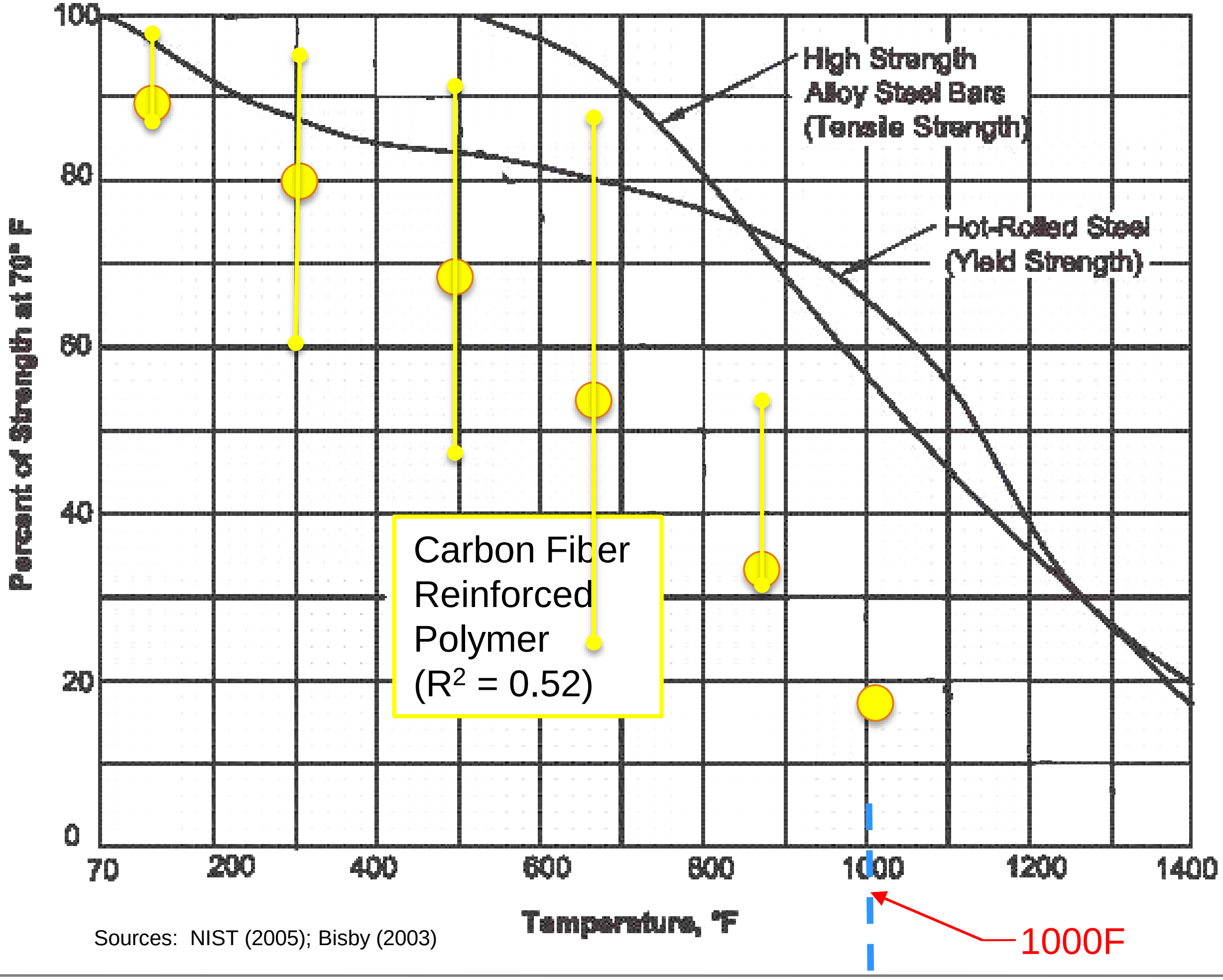
Roadblocks to Adoption of FRP
How Industry has Responded

- Lack of formal training
  - Evolution of specialty engineers
  - Growing comfort with delegated design approach
- Absence of non-manufacturer developed design guides
  - ICC Acceptance Criteria AC-125
  - Publication of ACI 440.2R
- Unfamiliar construction and testing procedures
  - Development of specialty FRP contractors
  - Evolution of firms with expertise in testing
  - Cost of testing can be significantly higher than expected

Roadblocks to Adoption of FRP
Fire Concerns Remain at Top of List

- Many architects still unfamiliar with performance under fire – so structural engineers are on their own
- Glass transition temperature (T_g) is around 160F (75C).
- UL-listing of some FRP products can mitigation concerns
- Cost of protective coatings alone in some UL-tested assemblies can exceed cost of installed, un-protected FRP system

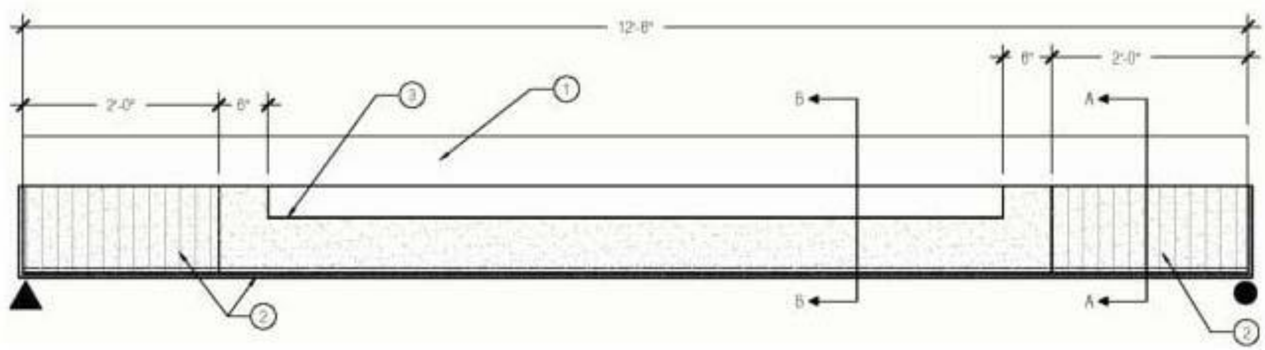
Effect of Heat on Steel and FRP Strength vs. Temperature

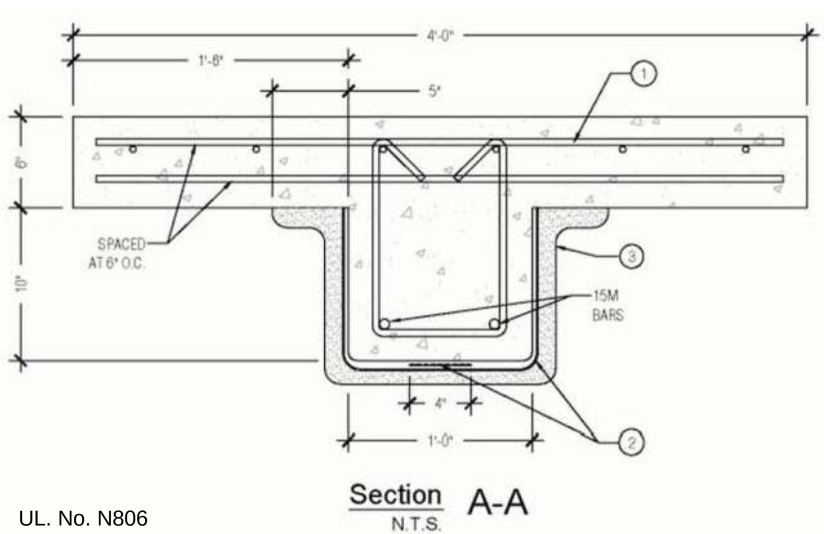


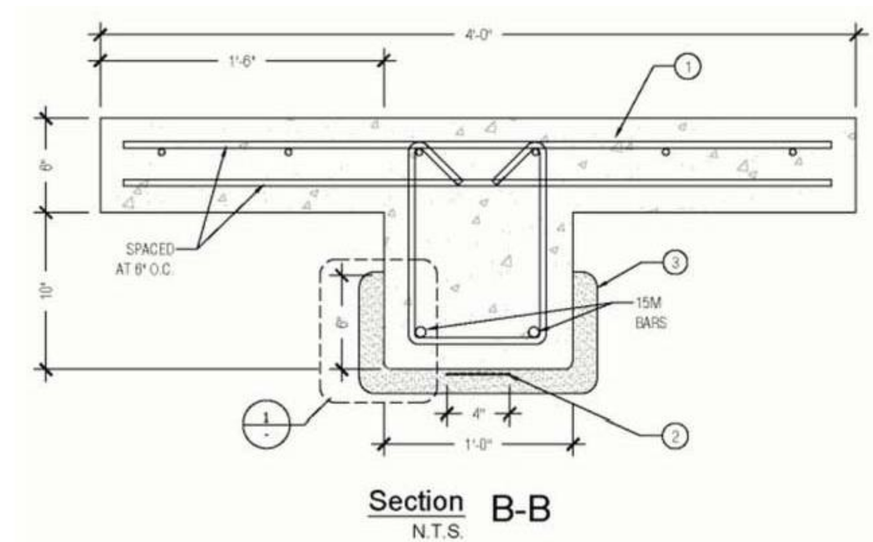
Sources: NIST (2005); Bisby (2003)

Sample UL Design for FRP-strengthened Beam Assembly

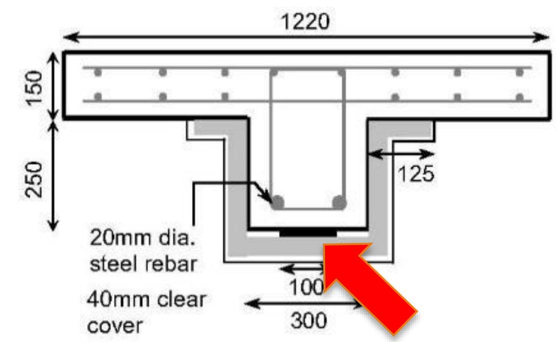
Unrestrained Beam Rating - 1, 2, 3, and 4 Hr

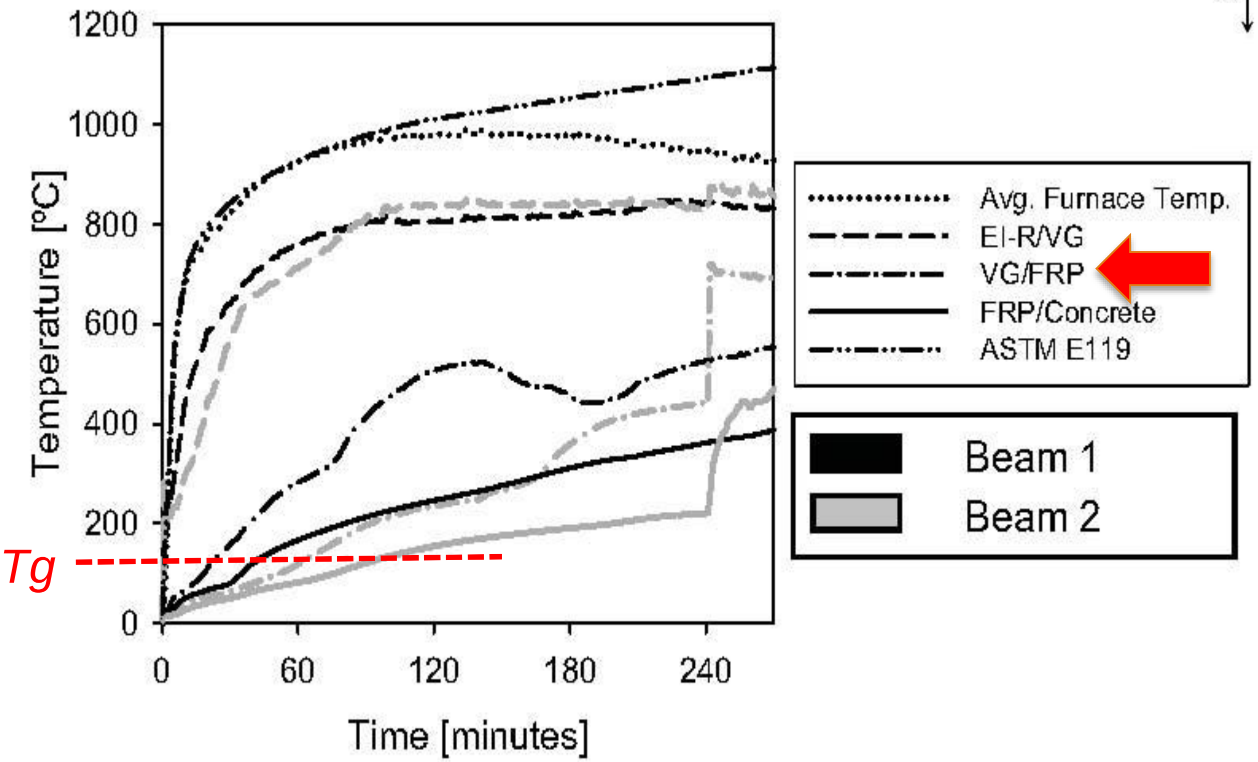






Williams, Bisby, Kodur, Su, and Green
Experimental Study of FRP under Fire





ACI 440.2R – 08
Strengthening Limit and Fire Consideration

- **Room Temperature** Eq. 9-1: Unrepaired structure needs to be capable of resisting 1.1(D) + 0.75(L), using normal f_y and f_c

$$(\phi R_n)_{existing} \geq (1.1 S_{DL} + 0.75 S_{LL})_{new} \qquad (9\text{-}1)$$

- **Fire Condition** Eq. 9-2: Unrepaired structure needs to be capable of resisting 1.0(D) + 1.0(L), using reduced f_y and f_c due to fire

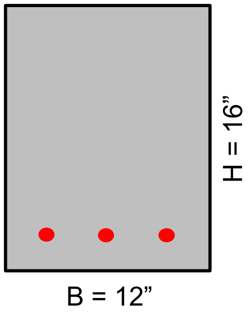
$$R_{n\theta} \geq S_{DL} + S_{LL} \qquad (9\text{-}2)$$

For certain D/L ratios and fire ratings, an unrepaired structure may have sufficient strength to avoid collapse during a design fire without thermal insulation over FRP

Unprotected FRP-Repaired Structures Currently in Service

Example Application of Eqs. (9-1) & (9-2)

- Existing Load: D_{old} = 85 psf, L_{old} = 60 psf
- Proposed Load: D_{new} = 90 psf, L_{new} = 80 psf
- Required Fire Resistance: 2 hrs



Step 1: Does proposed strengthening satisfy (9-1)?

$$(\phi R_n)_{existing} \geq (1.1 S_{DL} + 0.75 S_{LL})_{new}$$

$$(\phi R_n)_{exist} = 1.2\,(D_{old}) + 1.6\,(L_{old}) \quad >? \quad 1.1\,(D_{new}) + 0.75\,(L_{new})$$

$$= 1.2\,(85) + 1.6\,(60) \qquad 1.1\,(90) + 0.75\,(80)$$

$$= 198 \text{ psf} \quad > \checkmark \quad 159 \text{ psf}$$

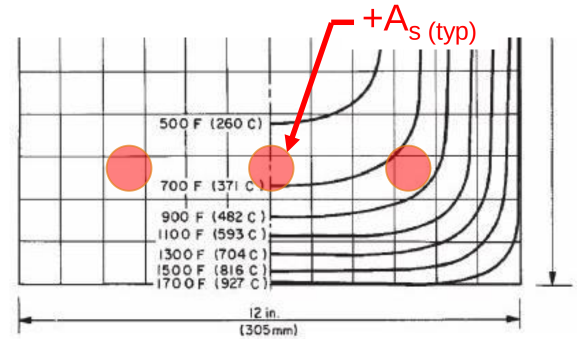
Example Application of Eqs. (9-1) & (9-2) (cont'd)

- *Step 2:* Does proposed strengthening satisfy (9-2)? $R_{n\theta} \geq S_{DL} + S_{LL}$

where $R_{n\upsilon}$ is nominal strength at elevated temperature

a) *From ACI 216.1, $+A_s$ bars reach about 750F after 2 hours*

b) *From temperature effect on steel data, at 750F, $F_{y\upsilon}$ = 78% of $F_{y(room)}$*



$$R_{n\upsilon} = \left[\frac{1.2(Dold)+1.6(Lold)}{\phi}\right] x\ 0.78 \quad >? \quad 1.0\ (Dnew) + 1.0\ (L_{new})$$

$$\left[\frac{1.2(85)+1.6(60)}{0.9}\right] x\ 0.78 \qquad 1.0\ (90) + 1.0\ (80)$$

172 psf >✓ *170 psf*

∴ No fireproofing required on FRP

ACI 440.2R – 08
Other Considerations

- Section 1.3.2: The structural member without FRP should possess sufficient strength to resist all service loads during a fire.
- Section 1.3.2: Smoke generation and flame spread should be determined using ASTM E84 and needs to satisfy building code criteria. This can typically be achieved using a suitable acrylic coating.
- Section 9.2.1: If thermal insulation is applied, overall structural performance of the assembly will be improved due to delayed strength degradation of the steel and concrete from heat. In other words, the insulation will protect the rebar much more than it protects the FRP.

Summary

- Changes over the past two decades require that our buildings be capable of withstanding fire and other extraordinary events
- Effects of fire on structural repairs are not well understood by most engineers for the following reasons:
  - Lack of formal training
  - Fire is not a typical design load; it produces a demand but also affects the capacity
  - Fire has a time and space domain – 4th and 5th dimensions
  - UL Directory can be cumbersome to follow
  - Technical literature uses unfamiliar words
- Architects don’t offer much assistance

Conclusions

- Fire protection needs must be assessed on a case-by-case basis:
  - Repairs for serviceability reasons seldom need protection
  - Repairs for structures with redundant load paths or which need a modest increase in load capacity may not need protection
  - Repairs for critical members or which provide significant increase in load capacity may be a candidate for analysis to evaluate need for protection
- Use of FRP presents special challenges due to degradation of epoxy at low temperatures
- Manufacturers' UL listings should be reviewed carefully to ensure design being specified complies with test assembly

Selected References

- ACI 440.2R-08, ACI 216.1-14, and ACI 562-13
- AISC 360, *Specifications for Structural Steel Buildings*, Appendix 4 - *Structural Design for Fire Conditions*, 2005
- ASCE 29-05, *Standard Calculation Methods for Structural Fire Protection,* 2005
- ASTM E119-15, *Standard Test Method for Fire Tests of Building Construction and Materials,* 2015
- *Best Practice Guideline for Structural Fire Resistance Design of Concrete and Steel Buildings*, NIST Tech Note 1681, 2010
- *Structural Engineers Guide to Fire Protection,* CASE Fire Protection Committee, 2008

Questions?

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