Fire performance of FRP-strengthened concrete systems

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Publisher's version / Version de l'éditeur:

Short Course on Response of Materials and Structures to Fires [Proceedings], pp. 1-49, 2009-05-20

Short Course
Response of Materials and Structures to Fires
May 20 - 22, 2009
Carleton University, Ottawa, Ontario

Fire Performance of FRP-Strengthened Concrete Systems

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Outline

- Structural Fire Safety
- Fire and FRP Materials
- Fire and FRP Structures
- Fire and FRP-Strengthened Concrete
- Recommendations for Design
- Application Cases
- Future Directions

Structural Fire Safety:

- The goal is to **limit the probability of death, injury, and property loss in fire**
- Modern codes place the emphasis on **life-safety objectives**
- Property protection is left to building owners
  - Ensure sufficient design consideration given to fire
  - **This is rapidly becoming more important…**

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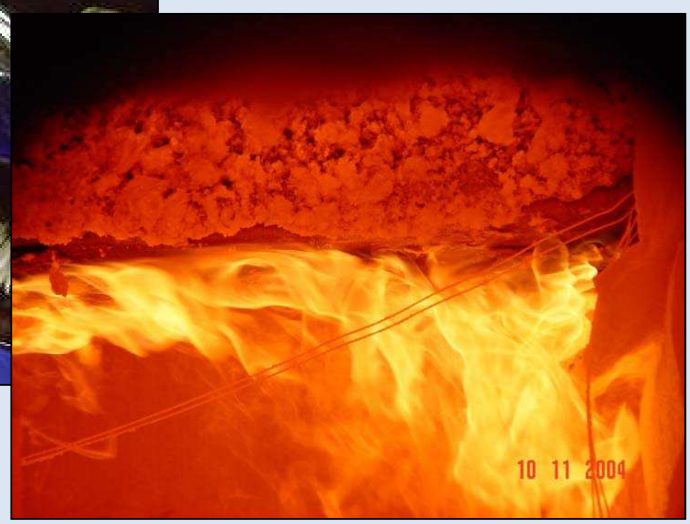
Structures in Fire: “Fire Resistance”

- Fire resistance is provided in selected members of a structure
  - Ensures that fire and smoke do not spread
  - Prevents structural collapse during fire
- **Fire Resistance (FR)**
  - Defined as the time to “**failure**” of a member when subjected to a “**standard fire**”
  - Evaluation of fire resistance
    - Fire testing
    - Prescriptive methods
    - Performance-based methods

What is “Failure”?

- Main **failure criteria** which define the fire resistance of structural members:
  1. Loss of load-bearing capacity
     - Must resist expected loads in fire
  2. Loss of fire separation characteristics
  3. ASTM - unacceptable temperature rise
     - Reinforcing/structural steel (temperature < 593°C)
     - 593°C is the **critical temperature** for steel (has approximately ½ its room temperature strength)
     - Unexposed surfaces (average rise < 140°C)

Fire and FRP Materials

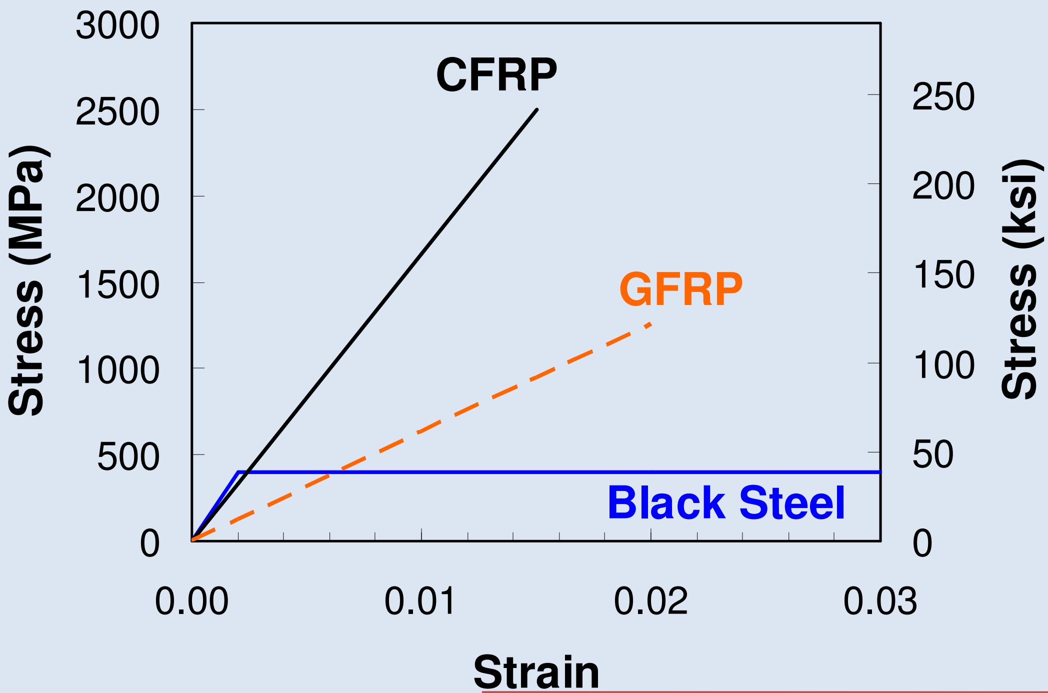


Fibre Reinforced Polymers (FRPs)

Fibres + Polymer Matrix = FRP

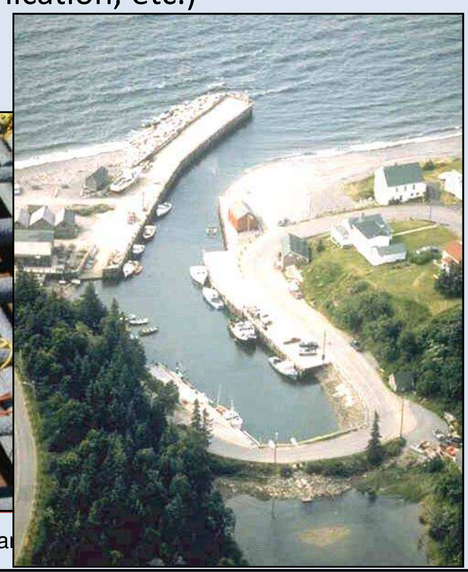
- Overall properties depend on:
  - **Mechanical properties of matrix**
  - Mechanical properties of fibres
  - Fibre volume fraction
  - Orientation of fibres
  - **Fibre-matrix interaction**
  - **Method of manufacturing**
  - Size of component
  - **Environmental factors**

e.g. Stress-Strain Response at Ambient Temperature



Applications of FRPs in Construction

- Internal reinforcement of concrete
  - Bridge decks
  - Marine structures
  - Non-magnetic applications (medical, communication, etc.)



Applications of FRPs in Construction

- Strengthening concrete, steel, masonry, timber
  - Flexure
  - Shear
  - Axial/Confinement

FRP characteristics at high temperature

- Organic nature of polymers → susceptible to combustion
- $\mathbf{T_g}$: Glass transition temperature is commonly taken as the performance limit for the FRP - Typically 70 – 100°C

FRPs & Fire: Major Concerns

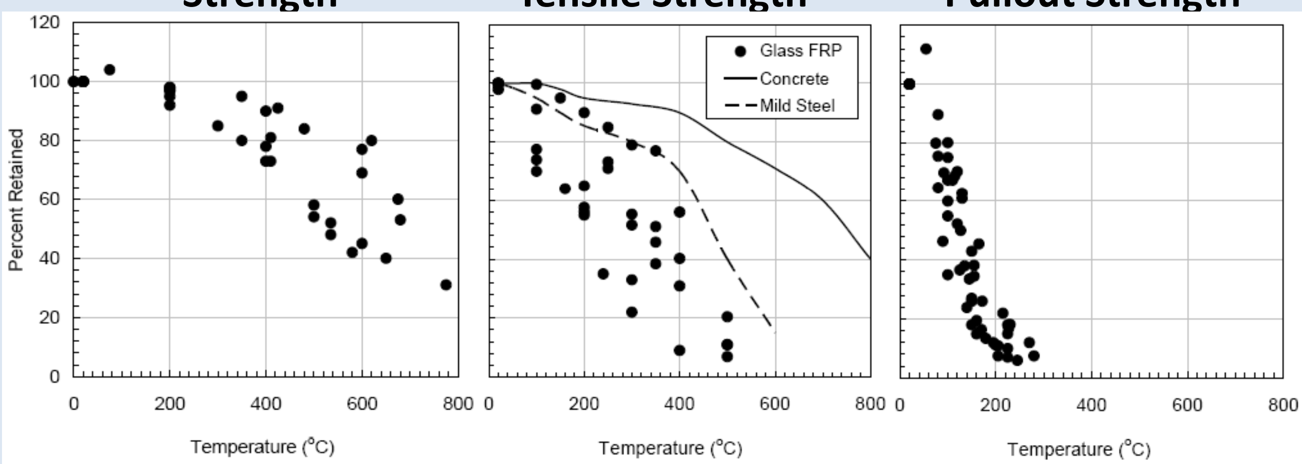
- Fire is recognized as a **critical** research need for FRP:
  - **a primary factor** preventing widespread application of FRPs in buildings

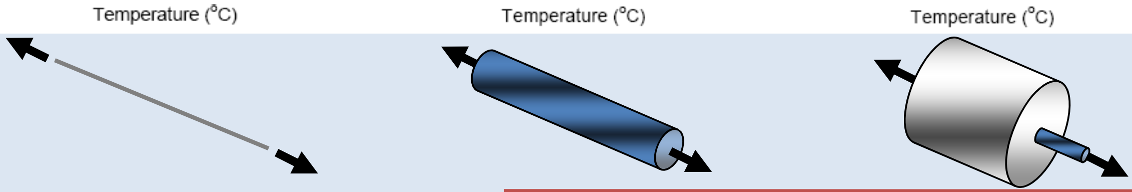
- Potential concerns during fire:

1. Loss of strength and stiffness
2. Loss of interaction (bond) w/ concrete
3. Smoke generation and flame spread

GFRP: Available Data (2005)

Glass Fibres Strength | **Glass FRP Bars Tensile Strength** | **GFRP Rebars Pullout Strength**

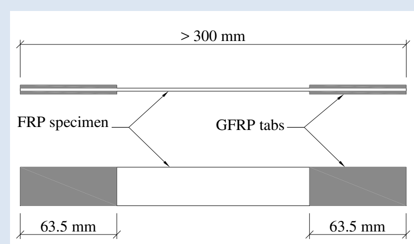




Note: Steady-state tests

Recent tests

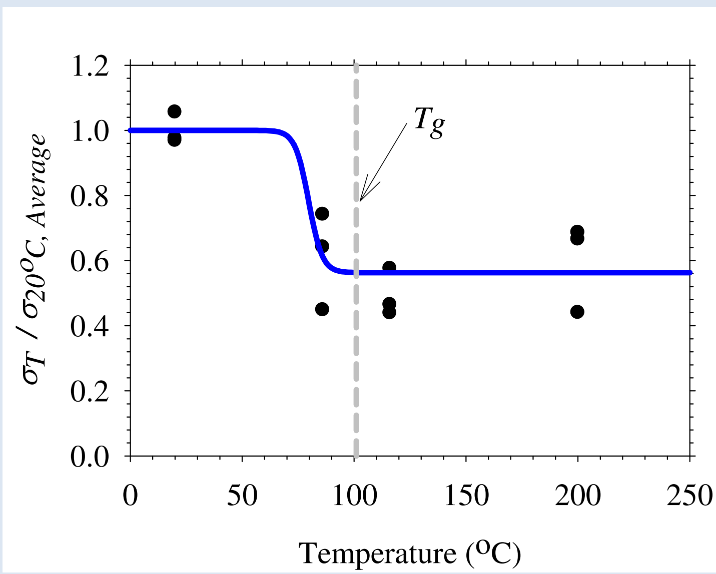
- Differential scanning calorimetry (DSC)
  - Polymer resin and FRP composite
  - Determine T_g
- Tension tests on FRP specimens
  - Tension tests on FRP coupons
  - Tension tests on single-lap FRP-to-FRP bond
  - Pull-apart bond tests on FRP-to-concrete bond
- Compression tests on FRP-wrapped concrete cylindrical specimens



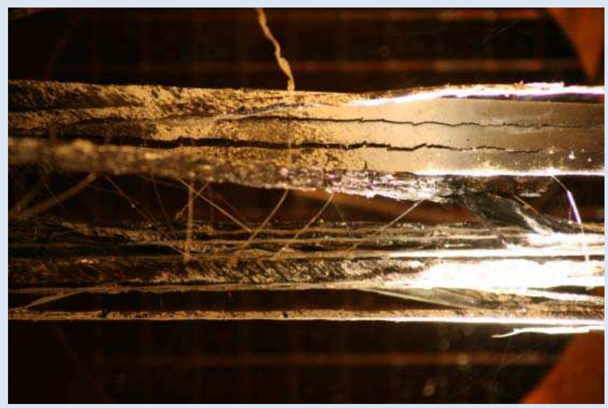
Results - strength

- Strength degradation

$$\frac{f}{f_o} = \left(\frac{1-a}{2}\right)\tanh\left(-b(T-c)+\left(\frac{1+a}{2}\right)\right)$$



Failure modes



86°C 200°C

Fire and FRP Structures

FRP Structures under Temperatures

- All FRP structures
  - Thick elements can char and protect FRP
  - Cellular floors protected/cooled with circulating water
  - Fire resistance: 90 to 120 min with cooling & 60 min without cooling
- FRP prestressed concrete
  - FRP always under high stress
  - Could be a critical situation
  - 26 minutes fire resistance for thin panels 45 mm tick

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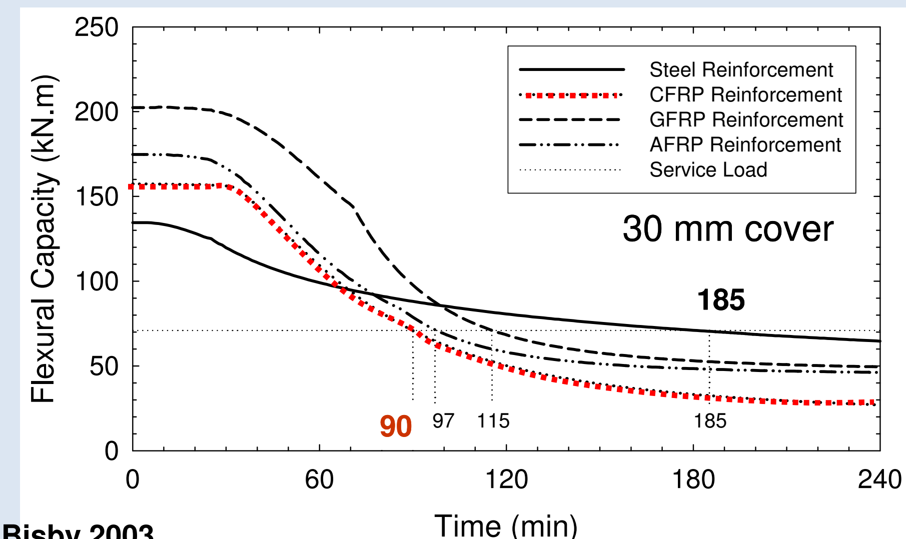
FRP Structures under Temperatures

- FRP reinforced concrete
  - More concrete cover required than steel?
  - Often over-designed for strength



Bisby 2003

FRP-RC Slabs under Fire: Designed for strength

Fire Resistance of FRP-Strengthened Concrete

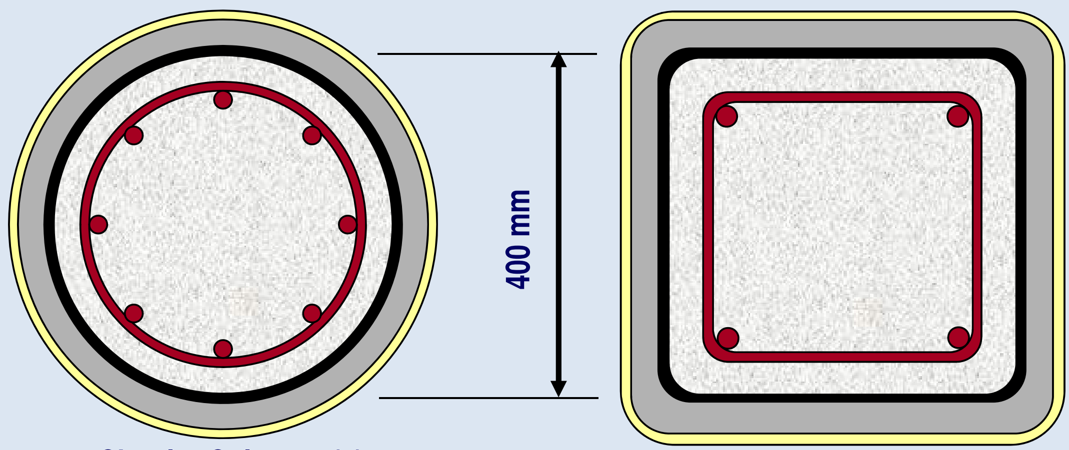
NRC-Queen's-ISIS Study

- Various member types:
  - FRP-strengthened RC slabs
  - FRP-wrapped RC columns
  - FRP-strengthened RC T-beams
- Experimental and numerical:
  - Intermediate and full-scale fire tests
  - Numerical thermal & structural responses
- Goals:
  - Understand fire behaviour
  - Provide fire-safe design guidance

NRC Column Furnace

Columns

Test specimens / FRP Wrapping / Insulation Schemes



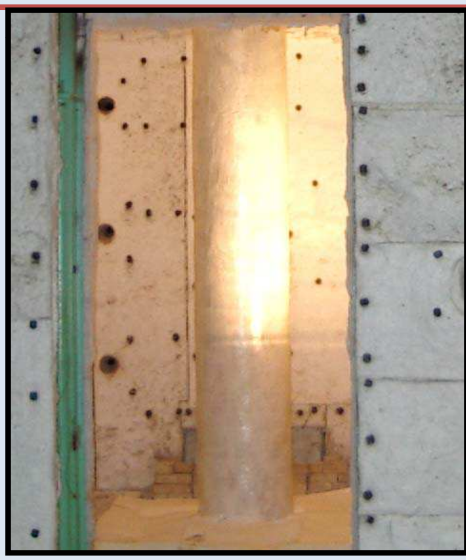
Circular Columns (4)

Square Column (1)

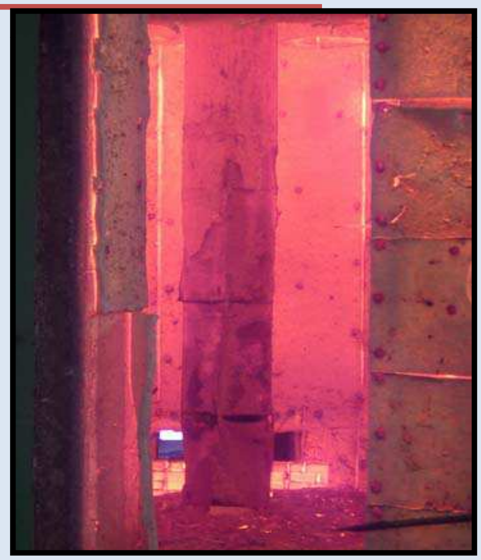
- Concrete
- Reinforcing Steel
- CFRP or GFRP
- Insulation
- Coating

ALL COLUMNS:
Length = 3810 mm
End Conditions = Fixed-Fixed
f'_c [circular] = 40MPa
f'_c [rectangular] = 52MPa
Concentric axial service load

Fire Test Results: Columns

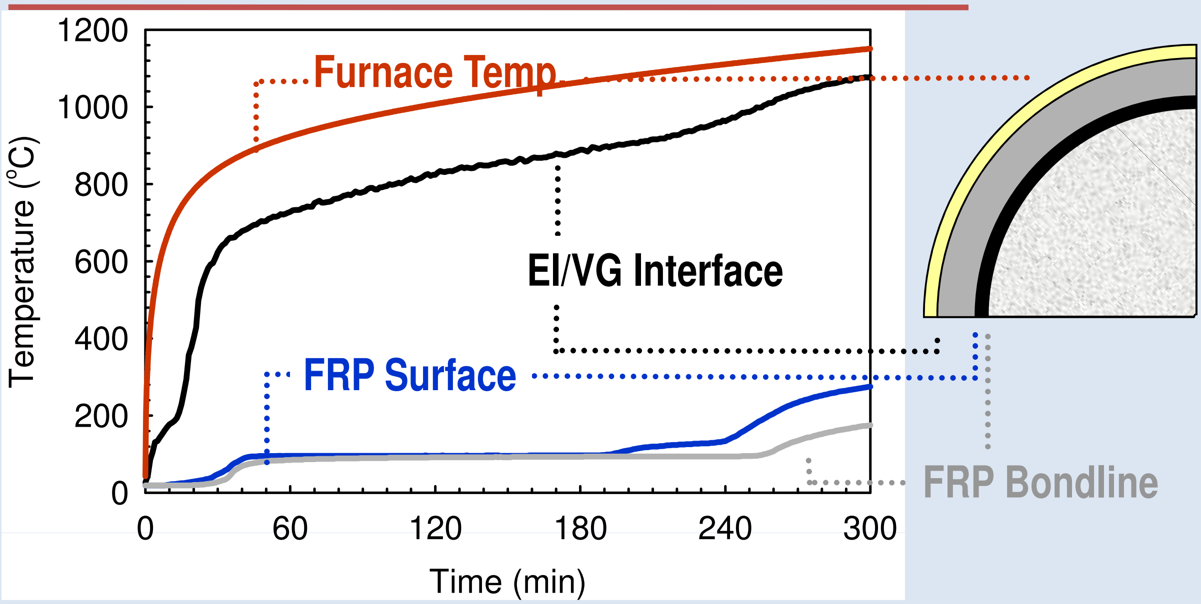


Column w/ 57 mm Ins.
Immediately Before Testing



Column w/ 57 mm Ins.
Immediately After Failure

Test Results for Column with Insulation Thickness = 57 mm

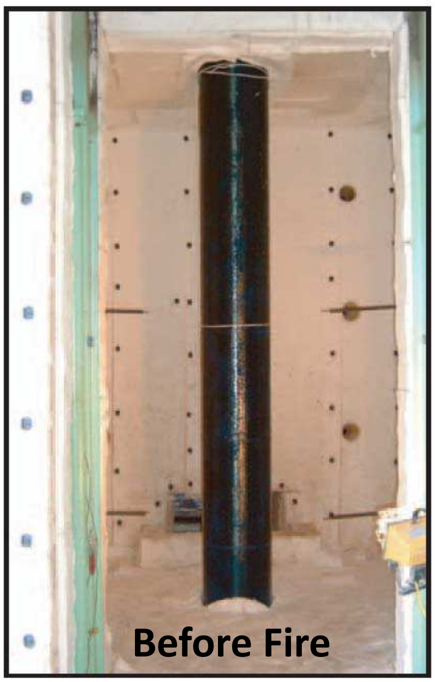


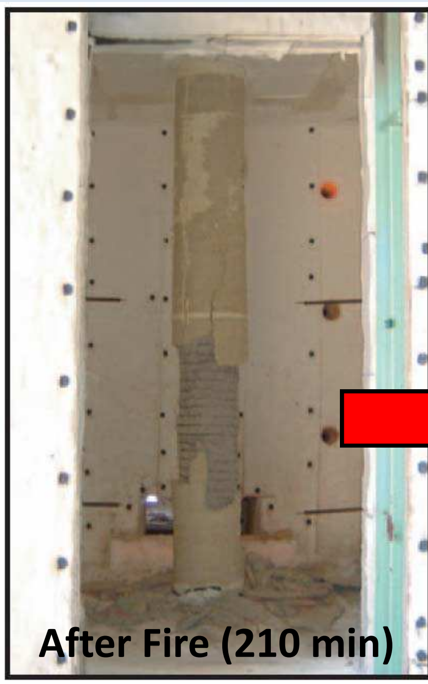
Temperatures recorded at various key locations in Column during fire exposure

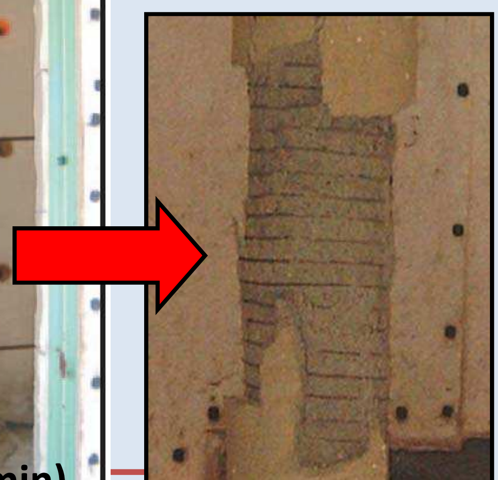
Unprotected Column after Fire

Fire Endurance = 210 min (3.5 hrs)

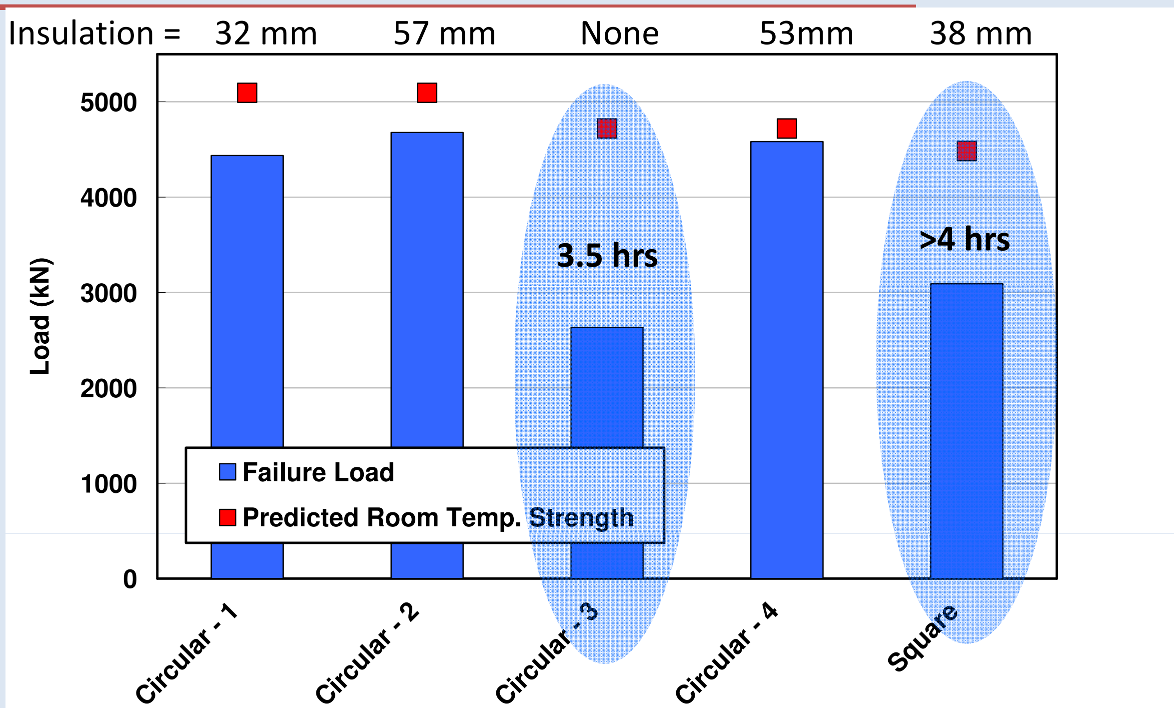
Code Fire Endurance = 4 hours







Column Strengths



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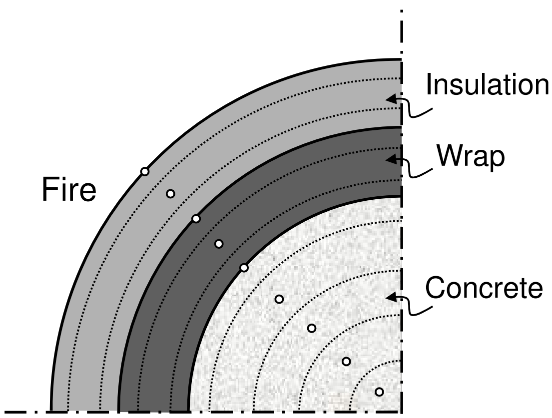
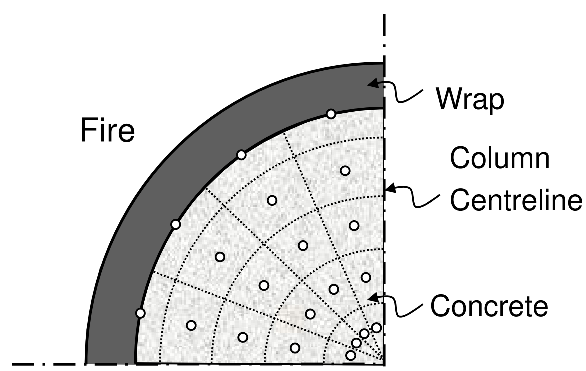
Numerical models (columns)

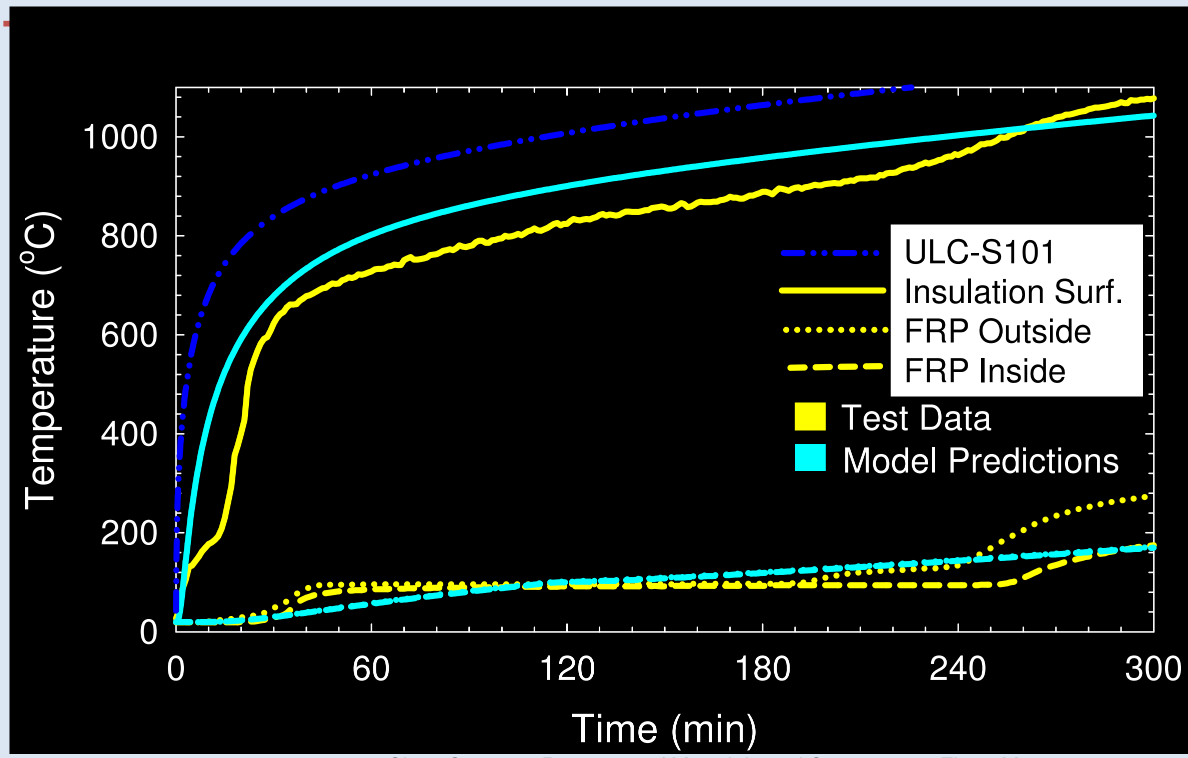


Schematic of discretization for heat transfer analysis



Schematic of discretization for load capacity analysis

Model results - column



Large-Scale T-Beams

- 4 tests in full-scale floor test furnace
  - CFRP for flexure
  - U-wrap GFRP anchorage
  - 4 supplemental insulation schemes

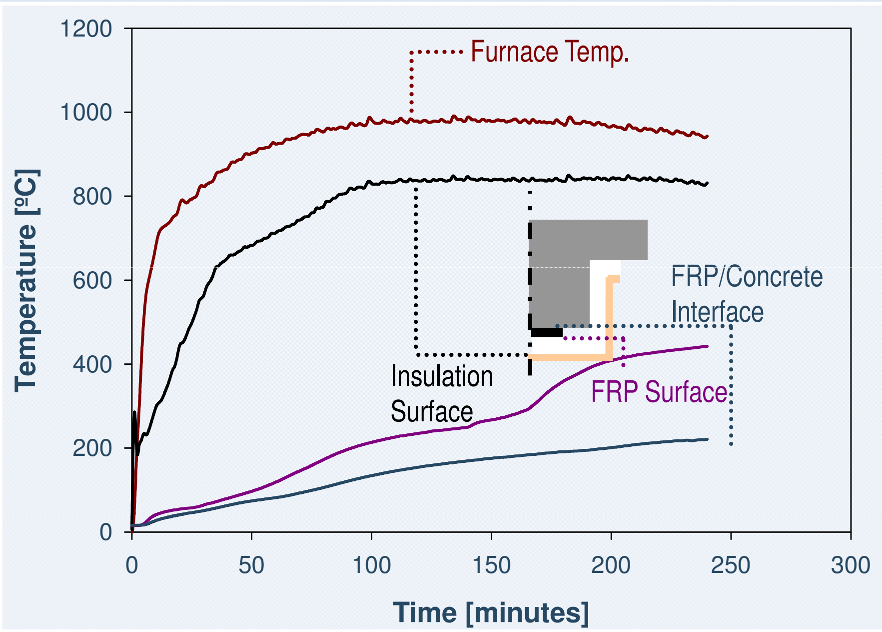
- Exposed to ASTM E119 standard fire
- **Subjected to sustained service uniformly distributed load**

Beam-Slab Assemblies - Before and after fire test

Beam before test

Beam after test and Failure

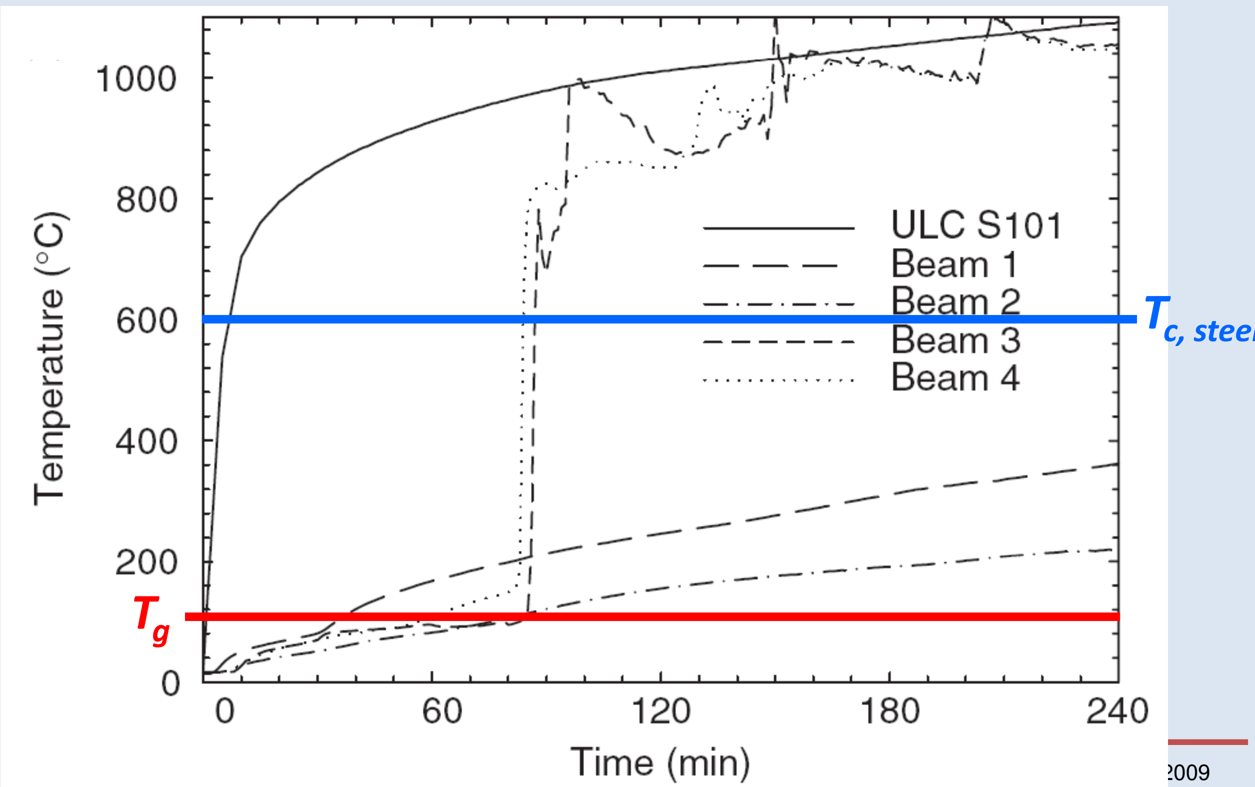
Beam-Slab Assemblies – Test Results



Insulation thickness: 38mm

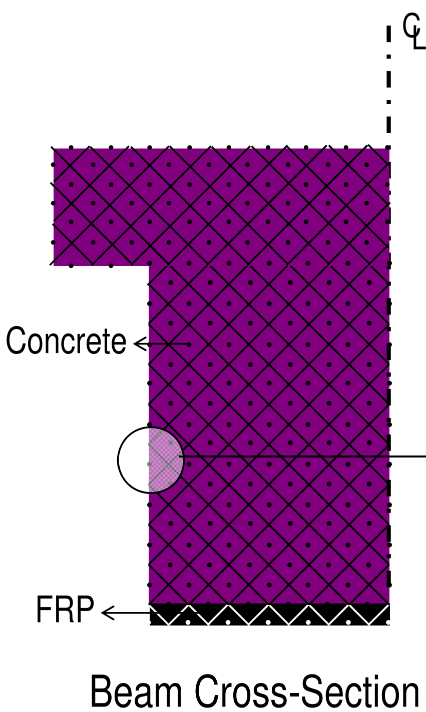
- $T_{FRP\text{-}AVG}$ < GTT (93°C) for **56min**
- T_{FRP} at 4hours: **442°C**
- T_{Rebar} at 4hours: **332°C** (< 593°C)
- $T_{Unexposed\text{-}Avg}$ at 4hours: **69°C** (< 140°C)

Beam Temperatures: FRP Bondline



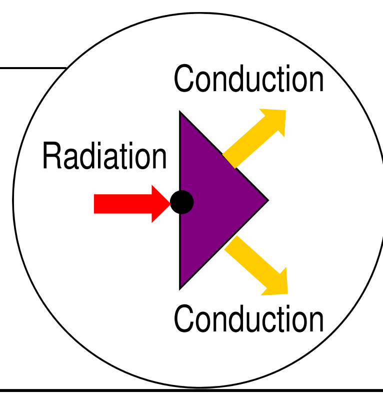
2009

Beam-Slab Assemblies - Heat Transfer Models



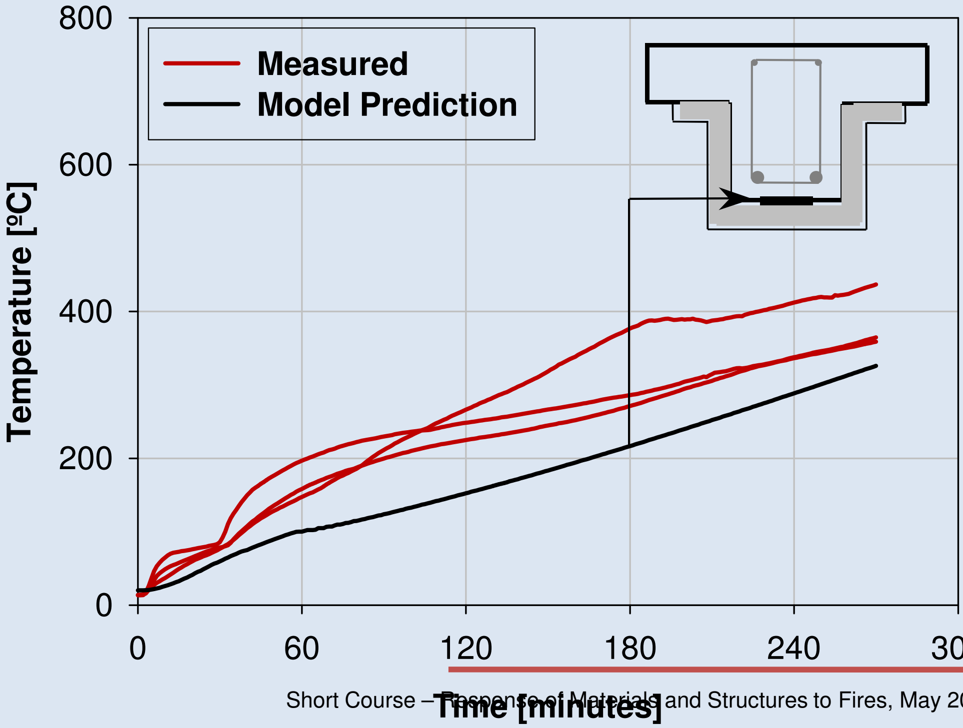
- Explicit finite difference method
- Discretize beam
- Thermal equilibrium for each element
- Accounts for variation in thermal properties and moisture content

Produces temperature distribution within beam section at any time during fire



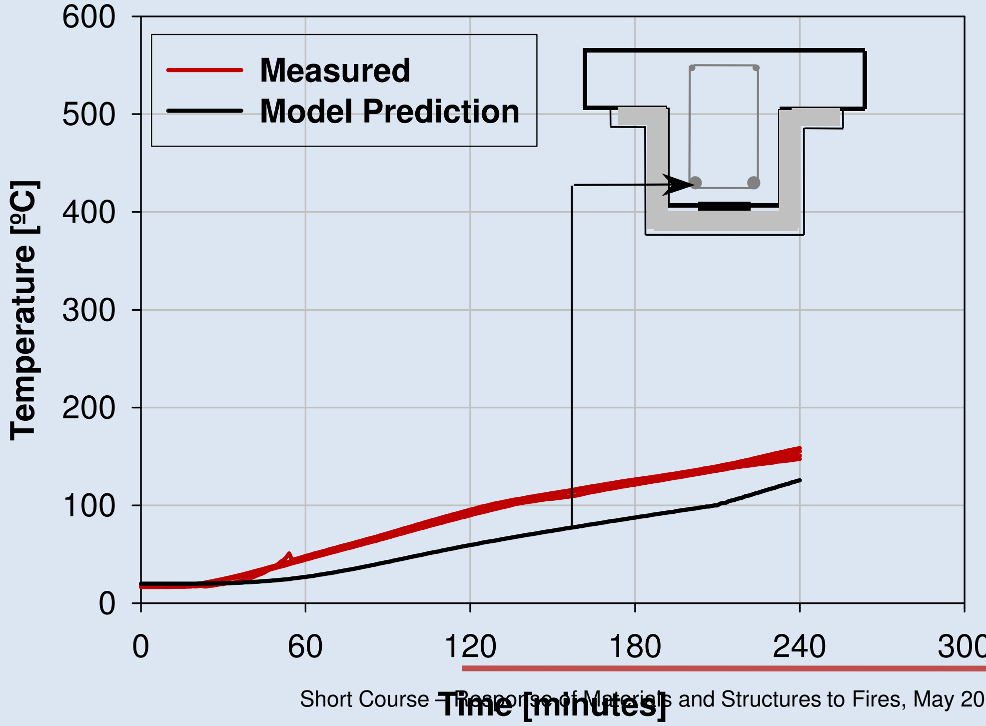
Beam-Slab Assemblies - Models

FRP-Concrete Bondline



Beam-Slab Assemblies - Models

Steel Reinforcement



Key Findings

- FRP-strengthened and adequately-protected concrete systems can achieve 4-hour fire ratings
- Insulation system remained robust during fire and effectively protect FRP systems
- Numerical models have been developed to predict FR of FRP-strengthened concrete systems

Design Implications

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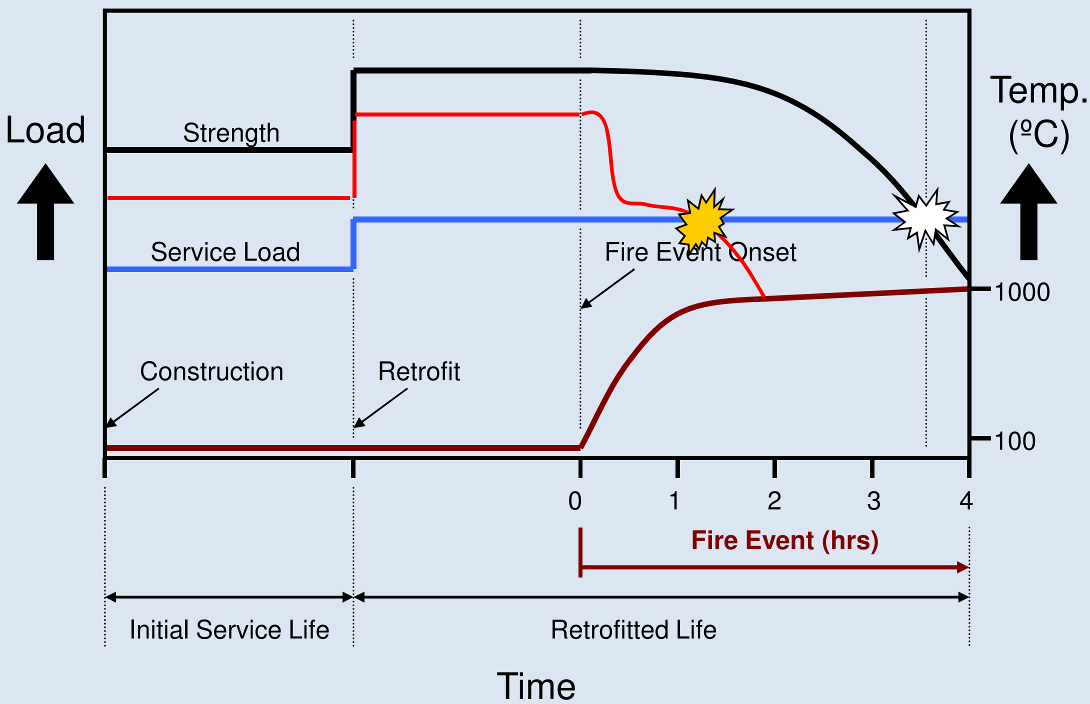
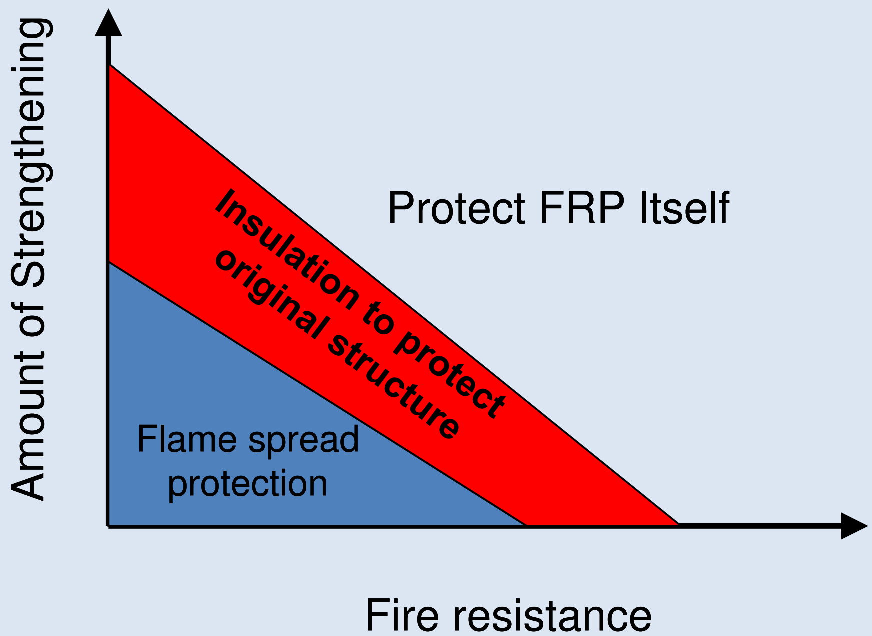
Philosophy for Fire-Safety



Conceptual design approach



Fire Design for FRP

- Base design on behaviour of **member or structure** not material only
- Ensure flame spread and smoke generation requirements are met
- Fire testing
  - too expensive
- Performance-based design
  - best approach

Performance-based fire design

- integrated testing and numerical modelling
- consider potential combustion of FRP
- incorporate external insulation
- numerical models validated against tests
- ensure external insulation stays in place throughout fire duration (testing)
- define ***critical temperature*** for FRP

Fire Safety Design Requirements

- FRP strengthened members require supplemental insulation to resist increased service loads during fire
- FRP strength could be used in a fire situation if and only if the temperature of the FRP is kept below a “critical” temperature
- The nominal strength at high temperature should at all times be greater than the strengthened service load on members
- NB: no requirement that temperatures remain below T_g!

*Important Note

- Fireproofing for FRP strengthening systems is not necessarily

~~"one system fits all"~~

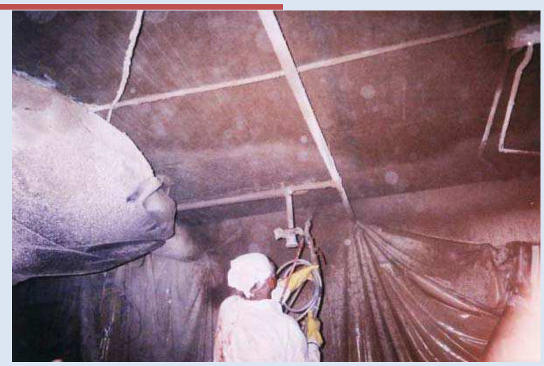
  – **Engineering checks are required to determine the fire rating of the existing structure with or without FRP and fire insulation**

Application Cases: Manufacturing Plant - Denver

- Roof slab damaged by fire
- Repaired with 1 layer of CFRP sheets
- Insulation for 1 hour fire rating
  - Wire mesh
  - Spray applied

Application Cases: Bank Building - Vancouver

- Strengthening needed for increased loads
  - High-density filing system
- Repaired with 1 layer of CFRP sheets
- Insulation for 2 hour fire rating
  - Wire mesh
  - Spray applied



Future directions

- Material characteristics (particularly "critical" temperatures for FRPs)
- Improve FRP properties at high temperatures (e.g., increas of $T_{g,}$)
- Numerical and experimental studies for near-surface mounted (NSM) reinforcement systems
- Design guidelines for all types of systems
- Detailing
- Sensing in fire

Acknowledgements

- The technical staff of Queen's University and the National Research Council
- Queen's University
- ISIS Canada
- National Research Council of Canada
- Fyfe Co. LLC
- BASF

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Questions?