Rational design for FRP strengthened reinforced concrete structures in fire

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Rational Approaches for Fire Resistance Design of Concrete Structures

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The Leverhulme Trust

Outline

- FRP and High Temperature
- Description of current ACI 440F recommendations
- Description of proposed changes to ACI 440F
- Loading during fire event
- Thermal modelling
- Structural modelling
- Examples

Examples of FRP

Unidirectional glass FRP bar

Carbon FRP prestressing tendon

Aramid FRP grid

Glass fibre roving

Carbon fibre roving

High strength fibres in a polymer matrix

FRPs & Fire: Primary 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

Current 440F Repair Guidelines - Fire

- “The strength of externally bonded FRP systems is assumed to be lost completely… unless it can be demonstrated that the FRP temperature remains below its **critical temperature** (for example, FRP with a fire-protection system)”
- “The critical temperature of an FRP strengthening system should be taken as **the lowest glass-transition temperature** T_g of the components of the repair system,”
- “The structural member without the FRP system should possess sufficient strength to resist all applicable service loads during a fire” **(1.0DL + 1.0LL)**
- “The fire endurance of FRP-strengthened concrete members may be improved through the use of certain resins, coatings, insulation systems, or other **methods of fire protection**”
- Reference is made to **ACI 216R** guidelines

Proposed 440F Repair Guidelines - Fire

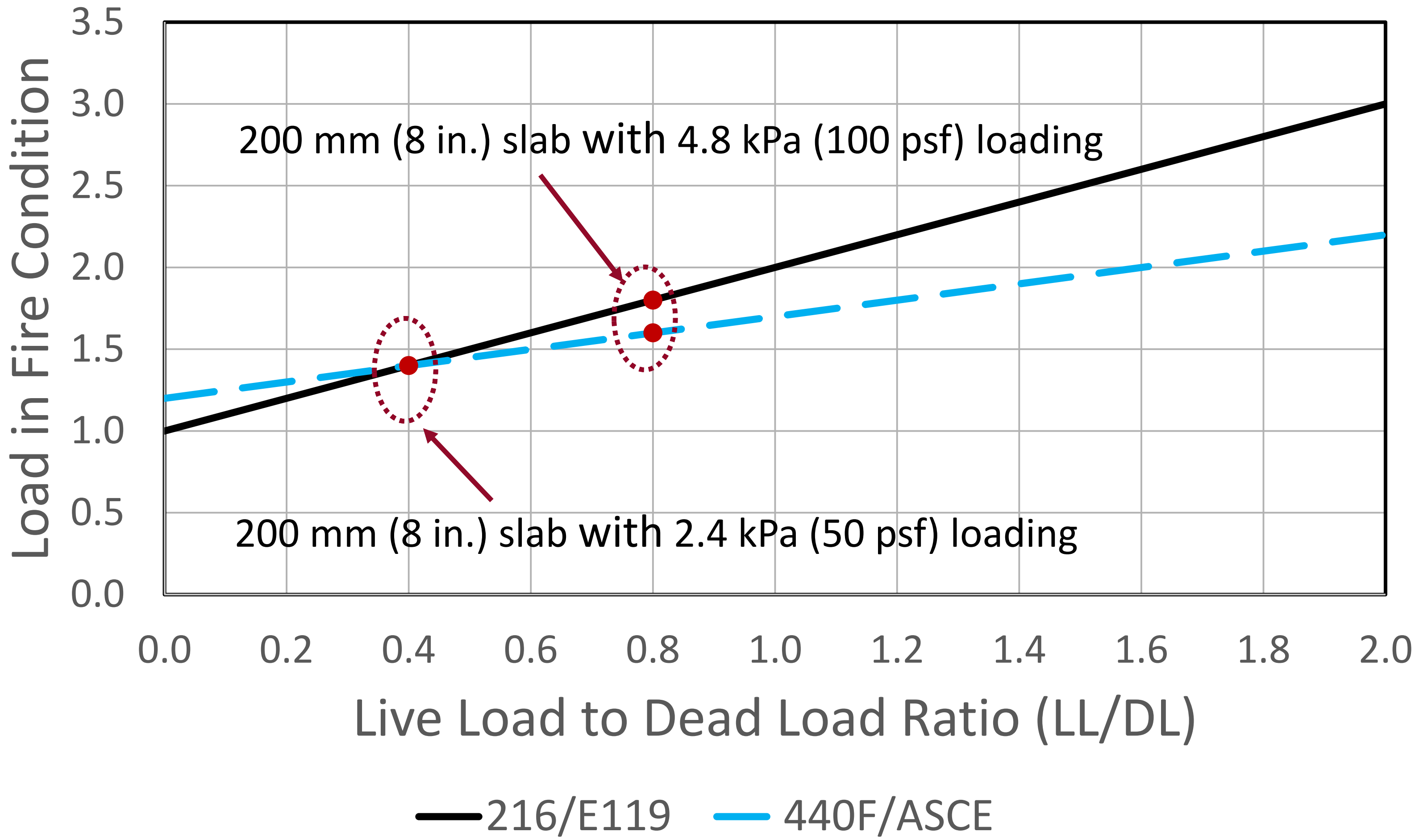
- "The strength of externally bonded FRP systems is assumed to be lost completely in a fire, unless it can be demonstrated that the FRP **will remain effective for the required duration of the fire** (for example, FRP with a fire-protection system)."
- "**In most cases**, the structural member without the FRP system should possess sufficient strength to resist applicable service loads during a fire" **($1.2DL + 0.5LL + 0.2SL + 1.0A_k$)**
- "The resistance should be computed for the time period required by the member's fire-resistance rating—for example, a 2-hour fire rating—and **should not account for the contribution of the FRP system unless the continued effectiveness of the FRP can be proven through testing.**"
- "Until better information on the properties of FRP at high temperature is available, the **critical temperature can be taken as the lowest T_g** of the components of the system."

Rationale for new load factors

- Old load factors for fire (1.0DL + 1.0LL) are based on ASTM E119 provisions for fire testing **(no statistical basis)**
- New ASCE 7 load factors are **based on probabilistic studies** and are applicable for new structures (Ellingwood)[1]
  - New loads have less than 5% probability of being exceeded in a given year
  - Average live load is 0.6 kPa or 12 psf (approx. 0.25 LL)

[1] Ellingwood, private communication with Tarek Alkhrdaji (August 2014)

Comparison of Loading Combinations

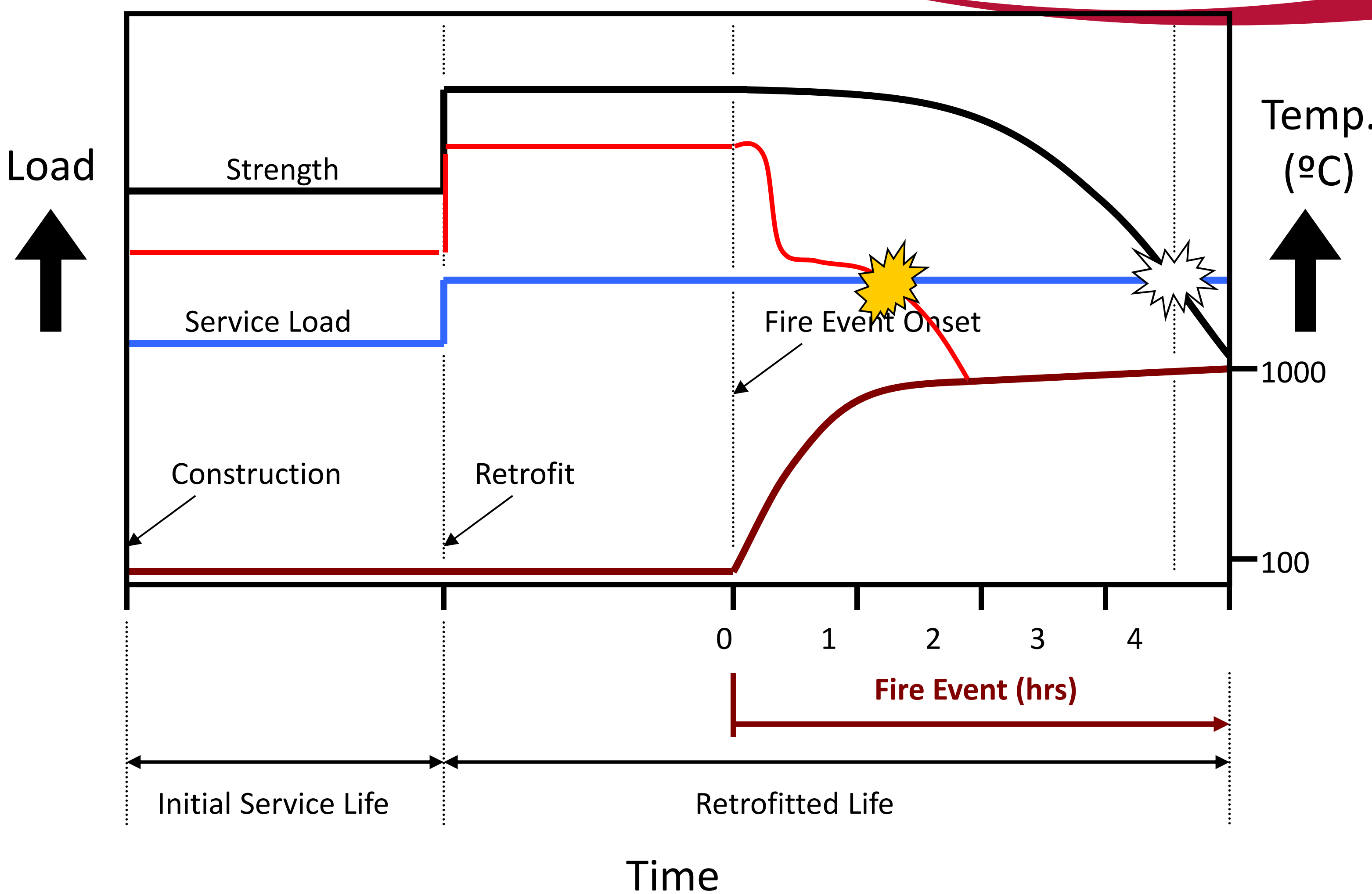


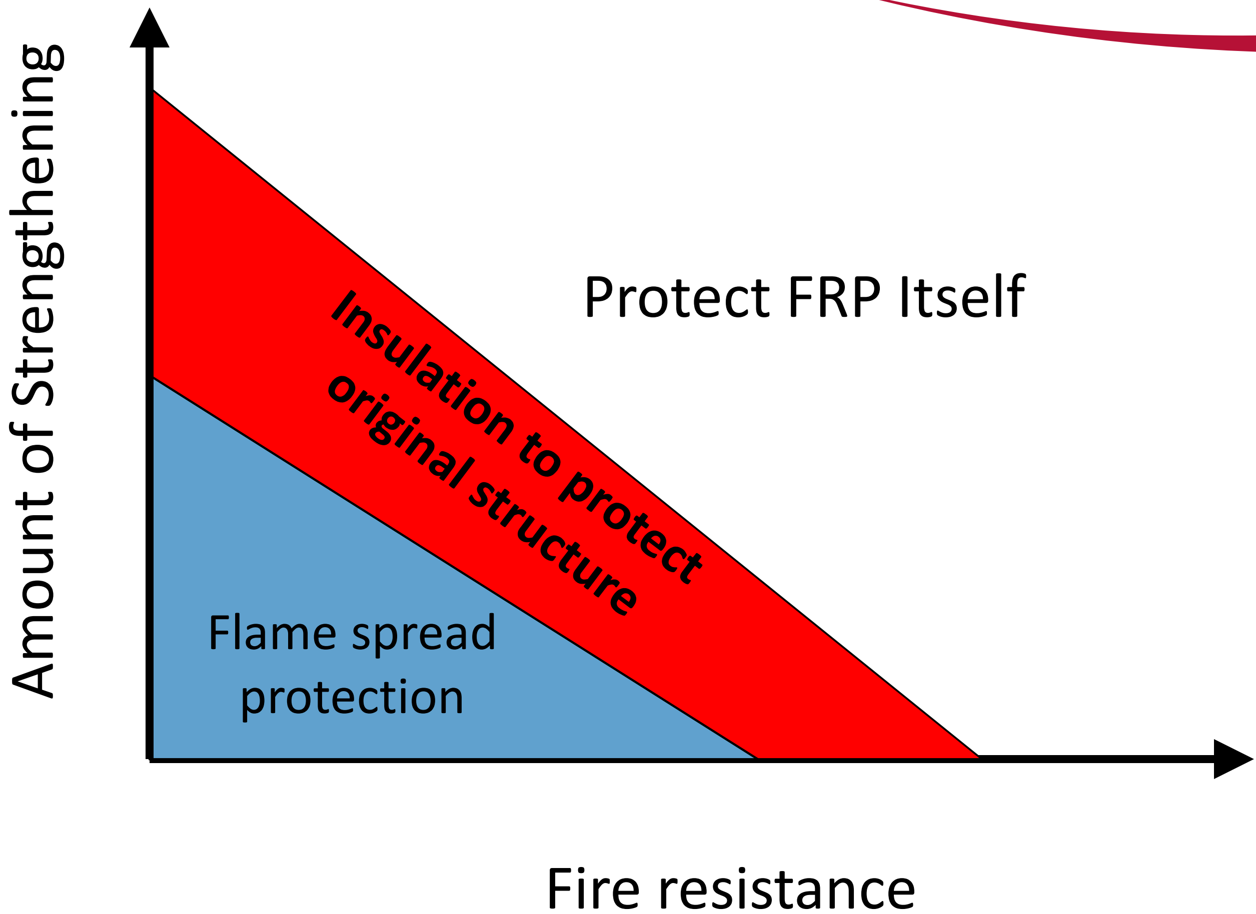
Procedure for finding fire endurance

Necessary analysis steps:

1. **Find temperatures** in member at different times during the fire exposure
   - Guides (ACI, Eurocodes), test data, analytical models, numerical tools
2. **Evaluate reductions in strength** and modulus of the materials (steel, concrete, FRP) depending on temperature – in most cases the FRP will not contribute
   - ACI 216, structural Eurocodes, research literature, testing
3. **Calculate member strength**
   - Classical plane sections analysis
   - Simplified methods (e.g. Eurocode 500^{o}C Isotherm Method)
   - Finite element methods

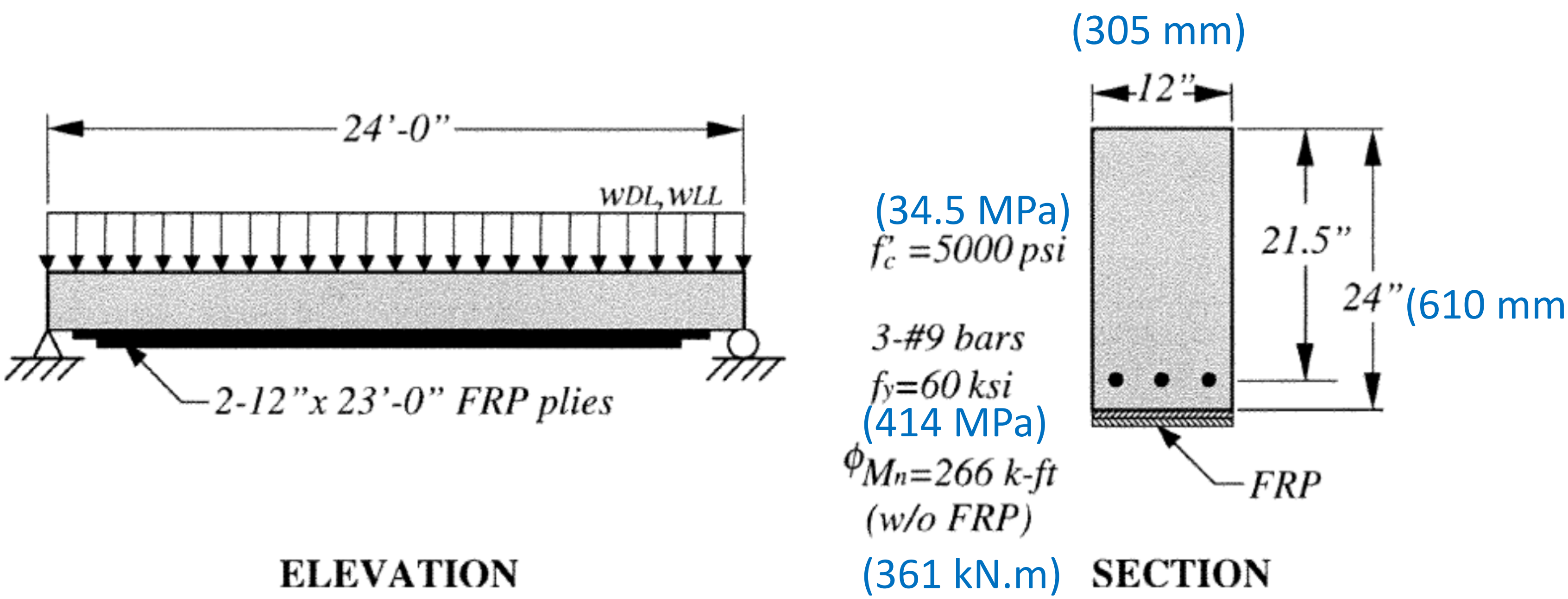
Philosophy for Fire-Safety





Amount of Strengthening
Protect FRP Itself
Insulation to protect original structure
Flame spread protection
Fire resistance

Design example (after ACI 440.2R)



A_s = 3.0 in^2 (1935 mm^2)

Analysis Approach and Assumptions

1. **Find temperatures at key**
   - FRP – determined from furnace ga
   - Steel reinforcement – determined
   - Concrete compressive stress block

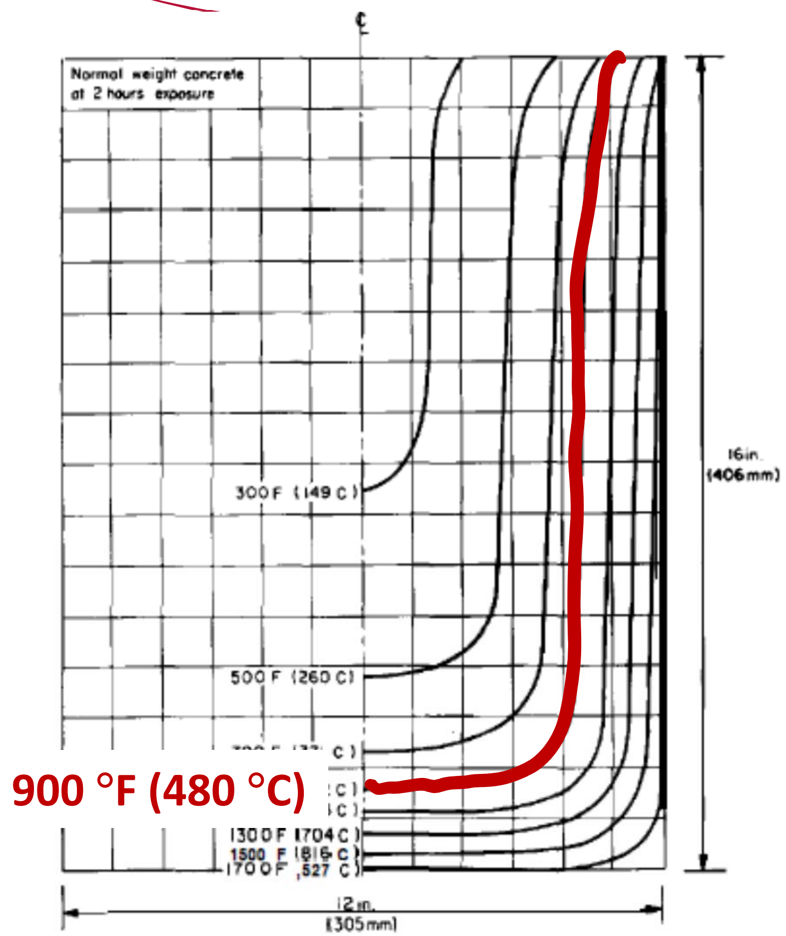


Fig. 7.2.10-Temperature distribution in normal weight concrete rectangular unit at 2 hr of fire exposure

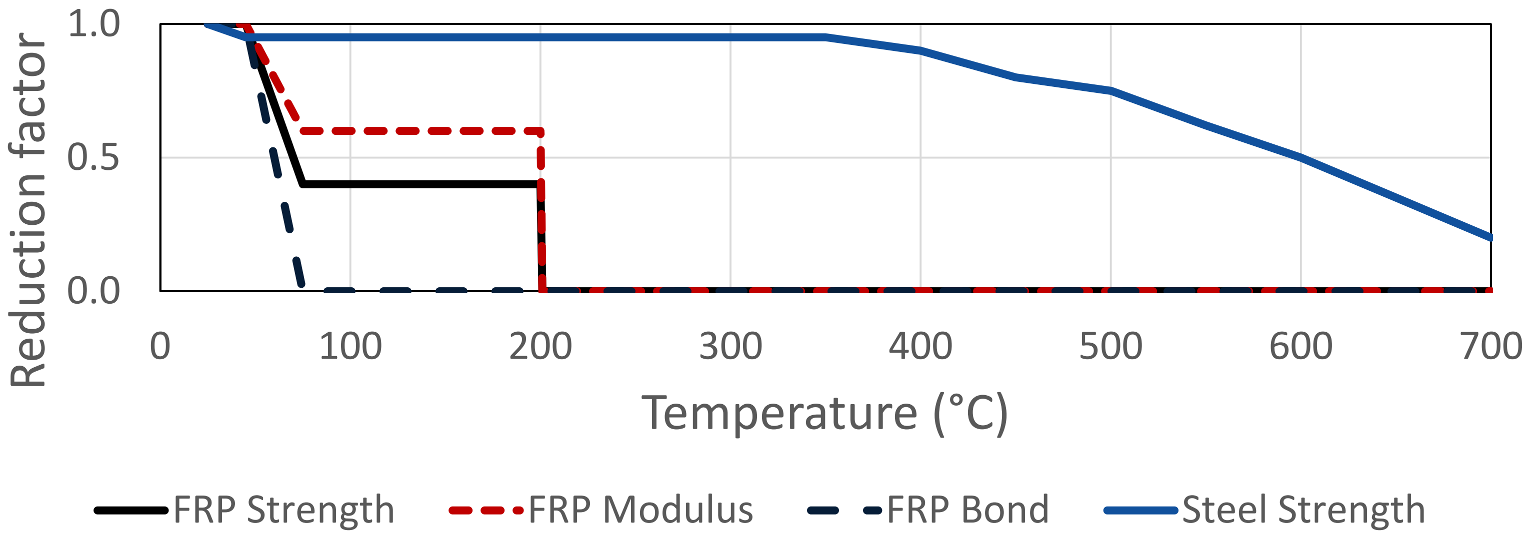
ACI 216 - 2 hours

Analysis Approach and Assumptions

1. Find temperatures at key locations

- FRP – determined from furnace gas temperature
- Steel reinforcement – determined from ACI 216
- Concrete compressive stress block – determined from ACI 216

2. Evaluate reductions in material strengths



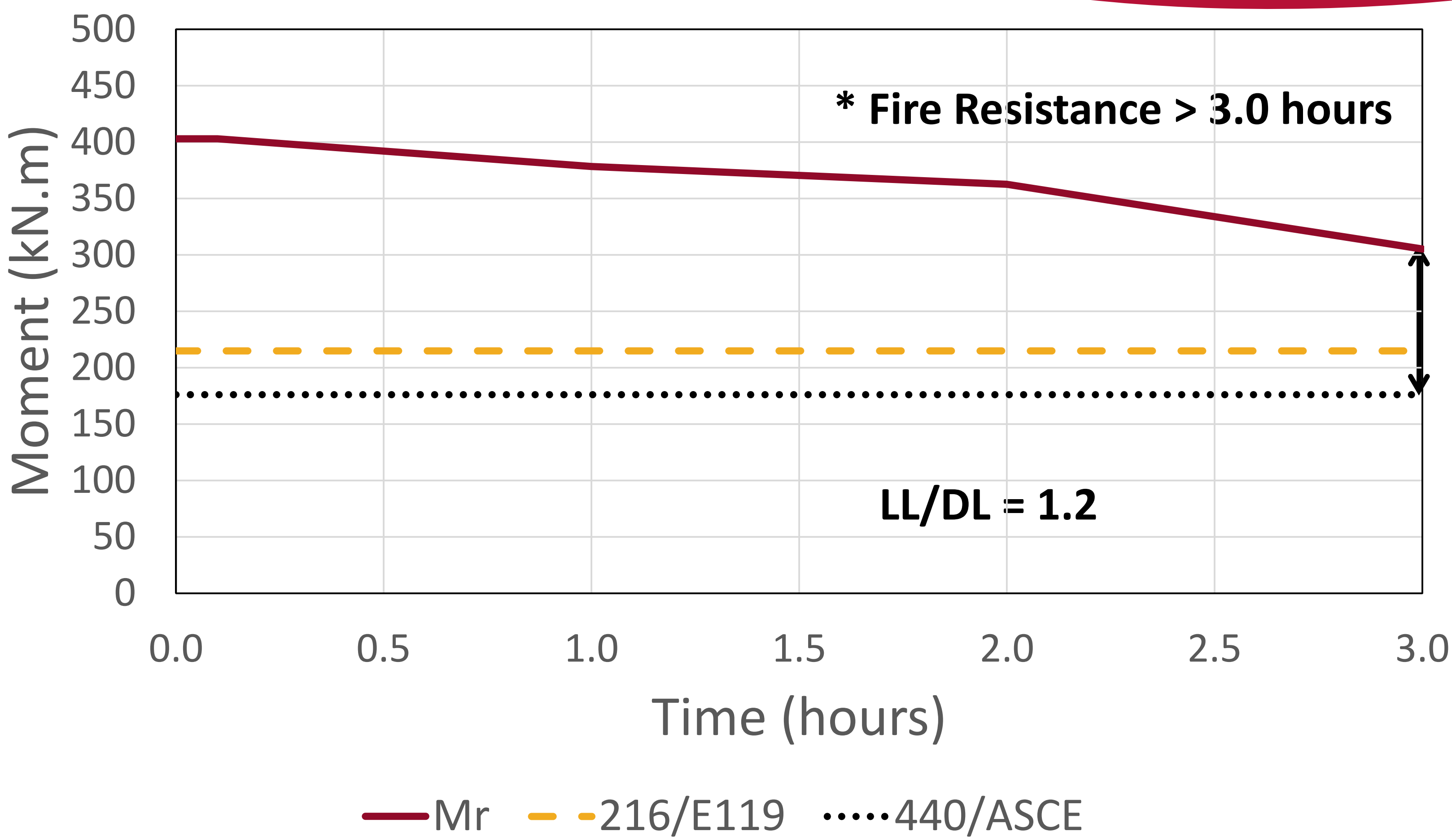
Analysis Approach and Assumptions

1. **Find temperatures at key locations**
   - FRP – determined from furnace gas temperature
   - Steel reinforcement – determined from ACI 216
   - Concrete compressive stress block – determined from ACI 216

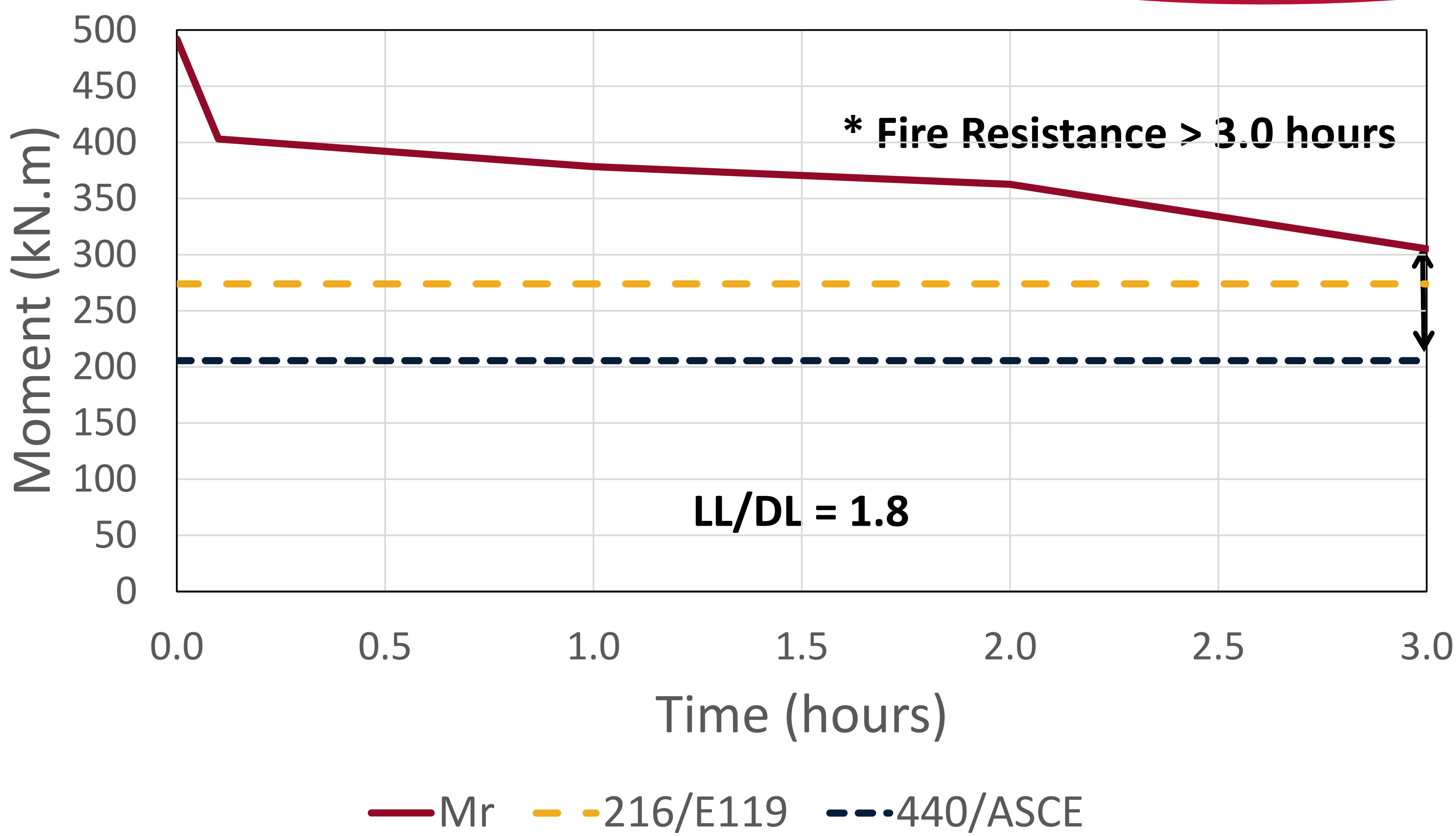
2. **Evaluate reductions in material strengths**
   - FRP – determined from Green et al. (2014) Bisby et al. (2005)
   - Steel Reinforcement – determined from ACI 216
   - Concrete compressive stress block – determined from Eurocodes

3. **Calculate member strength**
   - Classical plane sections analysis assuming full strength in 'residual' section
   - Eurocode '500°C Isotherm Method' used to treat compressive stress block width

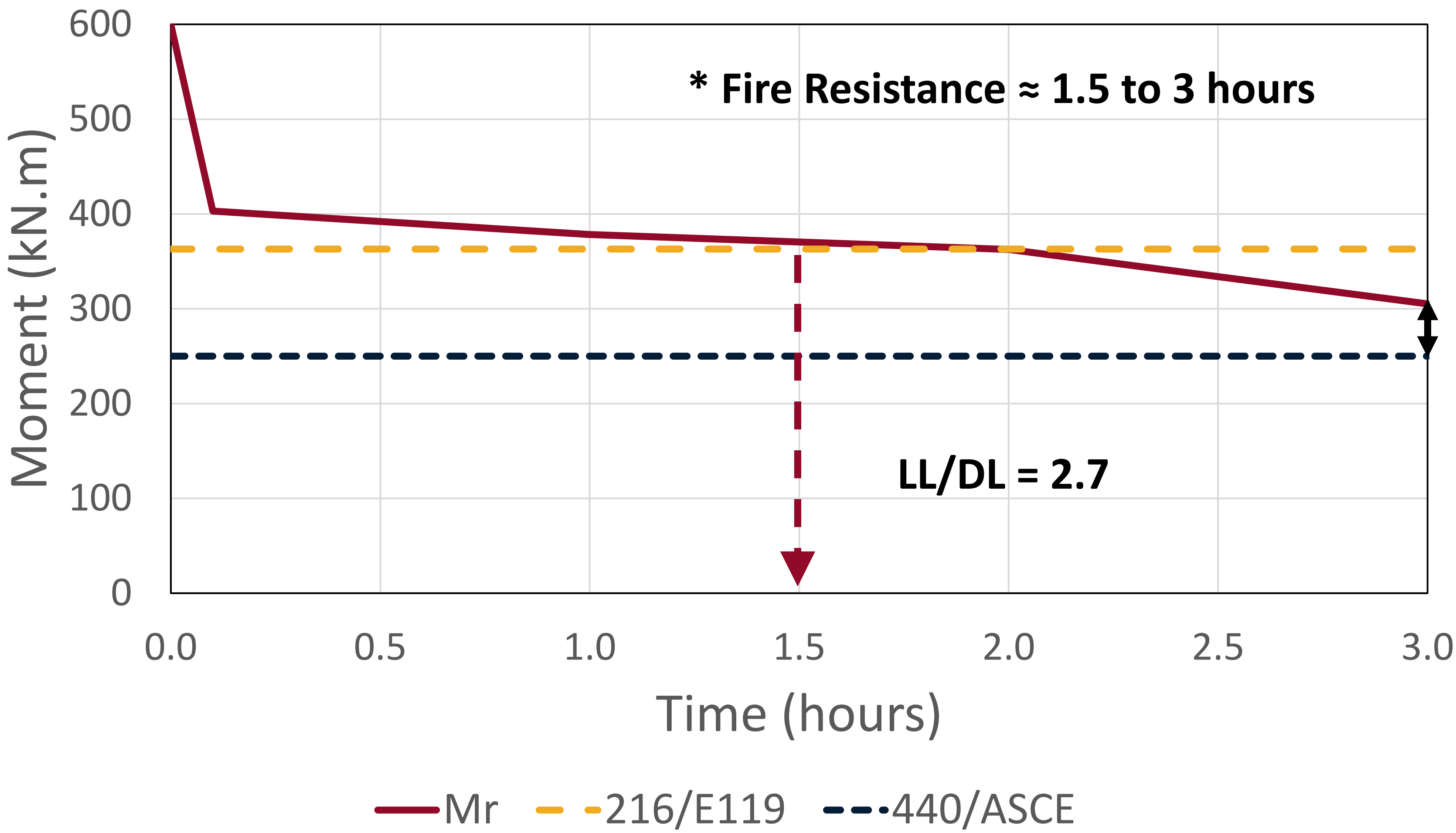
Unstrengthened beam in fire



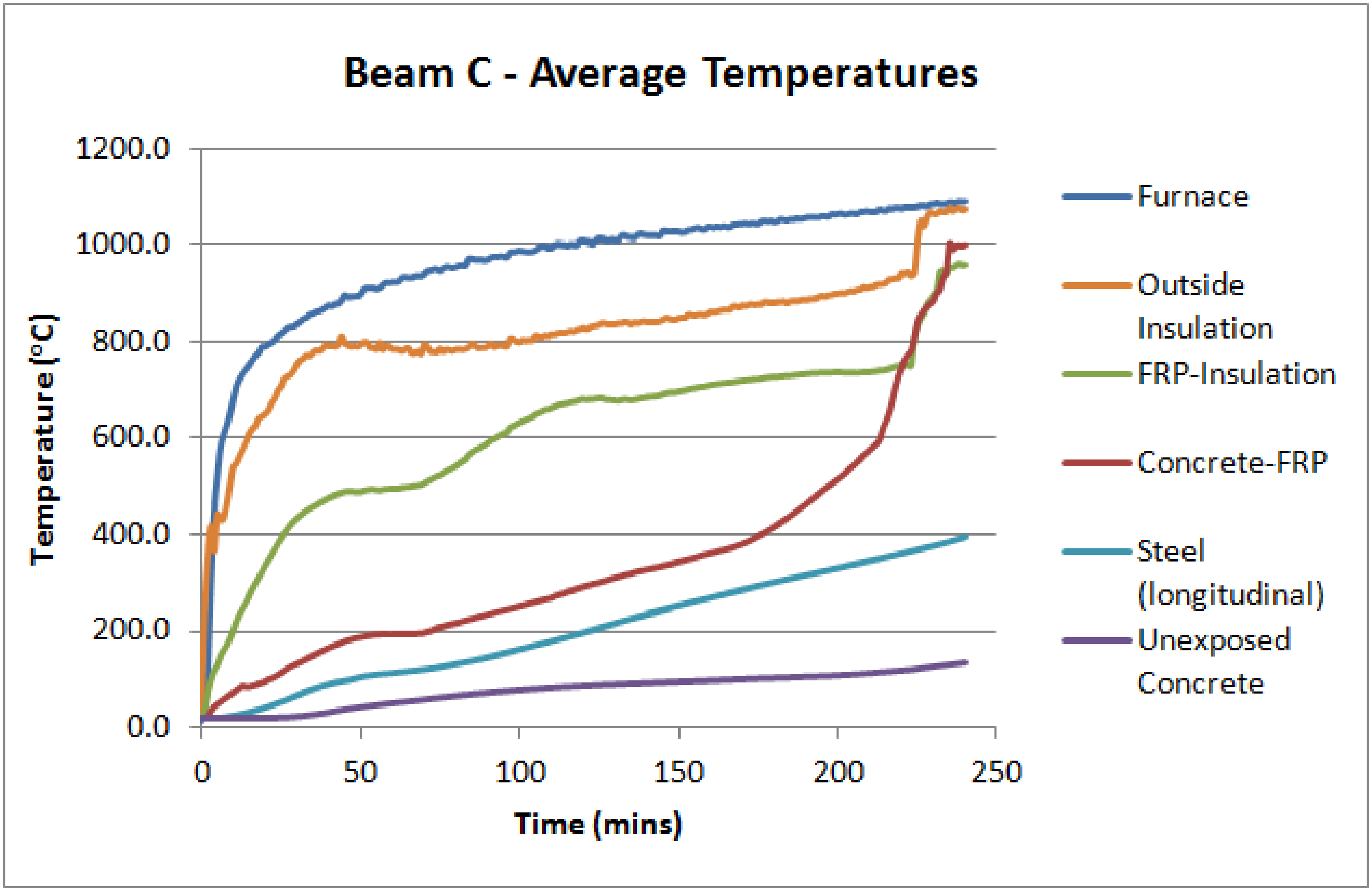
FRP Strengthened beam in fire



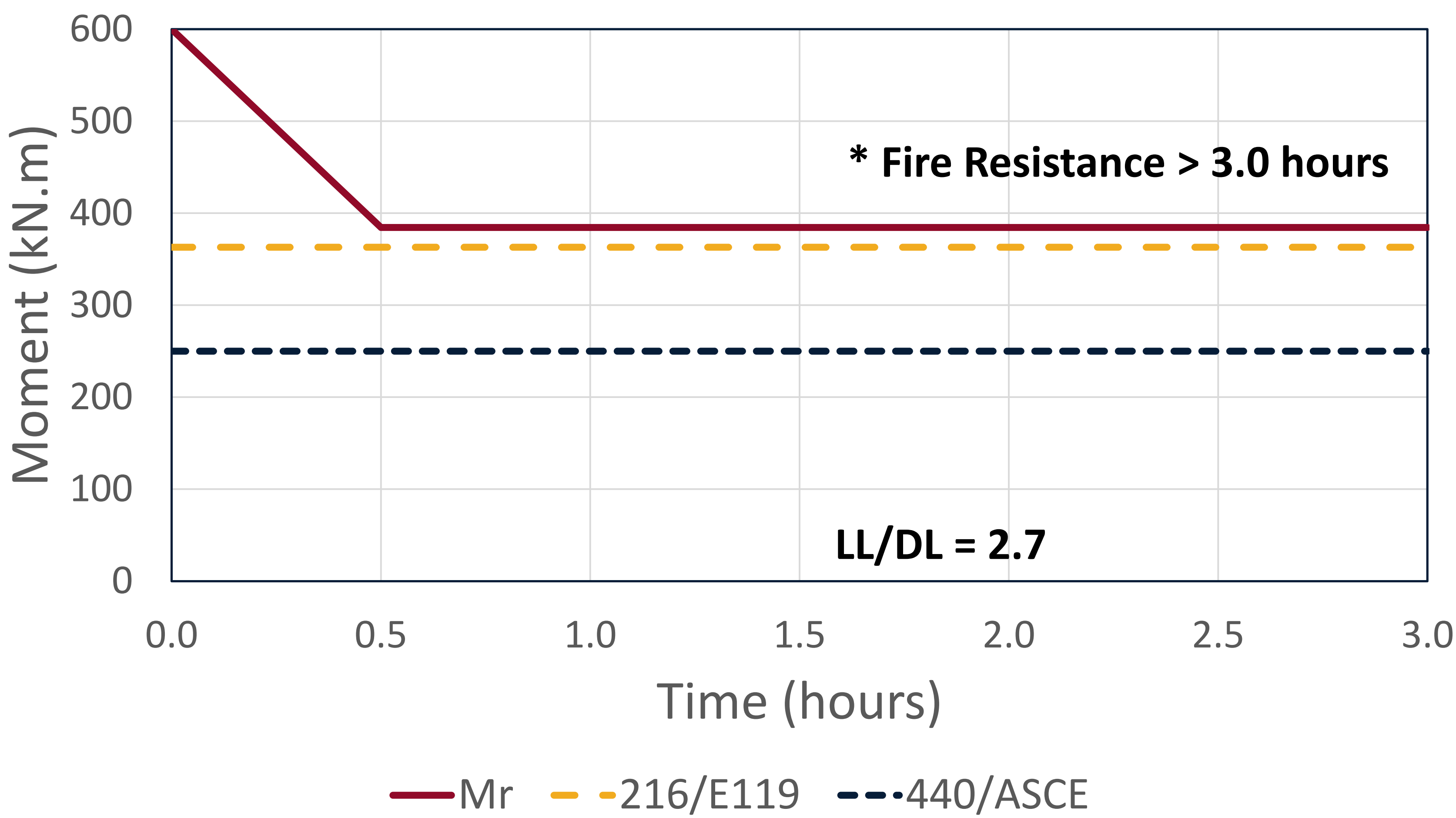
Beam FRP strengthened by 50% in fire



Insulation - Fire Test: Beam C (15 mm)



Beam strengthened by 50% in fire – with insulation



Conclusions

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- ACI 440.2R is proposing to modify the load demand equation for the fire limit state to harmonize with ACI 562 and ASCE 7

$$1.0DL + 1.0LL$$

$$\Downarrow$$

$$1.2DL + 0.5LL + 0.2SL + 1.0A_k$$

- Practical guidance has been given on how to determine the fire resistance of FRP strengthened beams, with or without supplemental fire insulation

- In most cases it is possible for FRP strengthened concrete structural elements to achieve satisfactory fire resistances

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Questions?

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