Conditional Assessment of Fire Damaged Structures: From Reconnaissance to Advanced Analysis

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Outline

- Background to Fire Problem
- Concrete Structures under Fire
- Need for Evaluating Residual Capacity
- Approach for Fire Damage Assessment
  - Classification of Damage
  - Reconnaissance to Advanced Analysis
- Methodology for Advanced Analysis
- Application - Case Study
- Results and Discussion
- Conclusions

Fire - Severe Hazard & Threat

- Fire cause thousands of deaths & billions of $ of damage yearly
- 2017 Data - Fire Losses in USA (NFPA):
  - 10,390 fire incidents
  - 3,520 fire deaths
  - 14,650 injuries
  - Total losses: $170 billion
- Fire represents most severe condition to a structure, and can occur as:
  - Primary event - natural origin (e.g., lightning, accidental)
  - Secondary event - Post EQ, blast, explosion, impact
- To mitigate fire risk a number of design & maintenance features
  - Fire prevention, suppression, & extinction - Sprinklers
  - Egress strategies - Notification, Exit paths
  - Structural fire safety - Compartments, Fire resistance
  - Structural Damage/Collapse
  - Only limited number of fires grow in to full scale fires
  - Structural collapse is very rare but structural damage is possible
  - Extent of damage hard to assess
- Need post-fire structural assessment
  - Ensure structural safety/stability
  - For re-occupancy of a Structure
  - Develop repair strategies
  - Assess extent of fire damage - insurance claims
  - Impossible to prevent all fires

Therefore, there is a need for post-fire damage assessment in structures!

Background

Major Fires in High-rise Structures

- Notre-Dame Cathedral Fire, France (April 15, 2019 6:30 pm)
  - Mortuary raids and arsons with high-metals state roof
  - Roof collapse, structural damage
- Plasco building, Tehran, Iran (Jan, 2017)
  - Steel building, 17 Story
  - Complete collapse after few hours of fire exposure
  - 50 story, concrete building, 250 sq ft (800 people)
  - Constructed in 1974 (major renovation in 2016)
  - 72 deaths, 40 injuries
  - Ignition of exterior cladding - facade?
- TU Delft, Faculty of Architecture building, NL (2008)
  - 2 tent buildings, 13 Story
  - Causing electric short-circuit in coffee vending machine - 5th floor
  - Building within 60 minutes of ignition
  - Resulted in partial collapse of the north section
- Windsor Tower, Madrid (2005)
  - 50 story tower, 26 floors above & 3 below ground
  - 14 floors made of ceramic, stone-painted composite panels above
  - Fire started at 21st floor, spread quickly
  - Overturned due to 5-levels of burning debris


- Impact followed by fire
  - 5 dead, 16 damaged (Mostly due to fire)

Significant structural damage; fire protection systems

Approach for Fire Damage Assessment

- Classification of damage
- Reconnaissance to Advanced Analysis
- Methodology for Advanced Analysis
- Application - Case Study
- Results and Discussion
- Conclusions

Background

Major Fires in Bridges - Bridges

- Interstate 85 fire, GA, US (March 31, 2017)
  - Reinforced concrete bridge
  - Fire started by arson (PVC pipes stored under the bridge)
  - Fire lasted for approximately 3 hours
  - Over 300 feet of the span suffered complete collapse 1 hour into the fire
  - Damage to adjacent spans
  - Steel girder bridge
  - Fuel tanker with 8,500 gallon of fuel cooled with guard rail
  - Collapse in 17 minutes into fire
  - Pre-stressed concrete girder bridge
  - Caused by railroad tanker carrying 30,000 gallons of Methanol Alcohol
  - Fire lasted for almost two hours
  - Bridge re-opened the next day

Significant structural damage, fire protection systems

Results and Discussion

- Structural Damage/Collapse
- Approaches for Fire Damage Assessment
- Methodology for Advanced Analysis
- Application - Case Study
- Results and Discussion
- Conclusions

Background

Grenfell Tower, June 13, 2017

- Fire occurred on June 13, 2017 at 12:34 am
- 72 deaths, 64 injuries
- Eight killed by fire, 4 injuries
- Over 200 firefighters and 40 fire engines
- Building features: 24-story concrete building
  - Located at North Kensington, London, UK
  - Constructed in 1974 (renovations in 2016)
  - 120 apartments (400 people)
- Fire causes:
  - Short circuit - faulty (bridge)/central gas system
  - Ignition of exterior cladding - facade?
  - Polyester powder-coated aluminium composite panels - Cheap, aesthetically uninviting
  - Rapid fire spread (60 mins to 24-story)
- Building problems:
  - Designed with one emergency exit
  - Lack of proper ventilation system
  - Many fire code violations - vented on fire safety
  - No sprinklers, Alarms were not activated
  - Firefighting equipment not checked for Y
  - Warning of fire risk - dismissed by owner
- Lessons learned:
  - Fire spread control (compartments)
  - Overall occupancy asked to "stay where you are"
  - Participating fire regulations - complied

350 feet

Fire by type occupancy based on annual average fire between 2010-2014

Building – demolished

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Fire by type occupancy based on annual average fire between 2010-2014

Building – demolished

Background
I-85 Bridge collapse, Mar. 30th 2017

- Fire occurred on Mar. 30th 2017 at 6:30 pm
  - No deaths or injuries
- I-85 (AL to VA) Bridge: Atlanta,
  - Made of prestressed concrete girders, RC piers
  - Built in 1953, reconstructed in 1985
  - Received a “sufficiency rating” of 94.6 on scale of 100 in 2015
  - Serves 243,000 vehicles a day
- Fire caused by burning of large PVC tubes stored under the bridge - Vandalism
- Bridge collapsed (in 30 min)
- Repair cost, $10 millions
- Time for repair: months.

Concrete Structures under Fire

- Concrete – Most widely used in construction material
- Fire Performance – Major requirement
  - Buildings, Parking garages, Tunnels
- Conventional concrete – Good fire resistance properties
  - High inherent fire resistance
  - Non-combustible
  - Low Thermal Conductivity (< 50 kcal/m·h·°C)
  - High Specific Heat (< 2 – Csteel)
  - Slower temp. induced degradation in strength & stiffness
  - High cross-sectional mass
- Concrete structures
  - Designed for 1 to 4 hours
  - Perform well under fire
  - Undergo minimal damage
  - Retain significant residual capacity
  - Hard to assess extent of damage!

Fire Resistance Design

- Need for Evaluating Residual Capacity
  - Post-fire occupancy and safety
    - Extent of residual capacity depends on number of interdependent factors
    - Damage short term and long term stability of the structure
    - Assess post-fire level of safety
    - To develop repairing or demolishing strategies
- Repair and retrofitting
  - Repair/strengthening measures
    - Reliable diagnosis can save money in repairs
    - Ensure safe environment for repair
- Insurance-damage assessment
  - Accurate estimate of economic losses or property damage

State-of-the-Art: Residual Capacity

- Residual capacity: Concrete structures
  - Highly variable
  - Quite complex and depends on a number of interdependent factors
    - Pre-fire (room temp.) properties & conditions
    - Structural and thermal conditions during fire exposure (heating, & cooling phase)
    - Residual properties of constituent materials
    - Incongruent fire resistance rating
    - Fire damage analysis tools not considered
- Knowledge Gaps
    - Assessment, Design & Repair of Fire-damaged Concrete Structures, The Concrete Society, 2007 (UK)
    - Sectional analysis methods with arbitrary ‘reduction’ factors
    - Do not account for structural parameters
    - Effect of residual deformations (plastic strains), temp. Induced bond degradation not considered
  - Lack of Advance Analysis Approaches
    - Based on current guidelines (The Concrete Society, 2007)
Modeling Residual Response

- RC Building under fire:
  - Complete building does not burn simultaneously
  - Limited compartments (floors) are subject to fire at any given time
- Modeling complexities:
  - Experience large thermal gradients across depth
  - Distinct material properties during heating and cooling
  - Thermal load, compressive strength
  - Load-induced thermal strain (LTS) are irreversible
  - Temperature-induced degradation in tensile and bond strength
  - Residual thermal & shrinkage strain
- Uncertainty in post-fire response:
  - Variability in fire exposure scenario
  - Load level, Material models, RC's
- Advance Analysis Approaches:
  - Both temp. history, accumulated material/structural damage, as well as conditions present during fire exposure
  - Influe

Conditional assessment:
- (Class A)
- Field inspection, observations
- Non-destructive testing
  - (Class B,C)
  - Rebound number measurement, Schmidt hammer test
  - Ultrasound pulse velocity

Rebound number measurement using Schmidt hardness tester

Case study: Hotel Aseman Fire, Iran

- Building features:
  - 22-story concrete building
  - Fire occurred on Aug. 3, 2019
  - No deaths
  - Significant structural damage to slabs & shear walls
  - Need repair and retrofitting
- Fire cause:
  - Occurred during renovation work

Fire Damage Assessment: Reconnaissance to Advanced Analysis

- Conditional assessment:
  - Reconnaissance:
    - (Class A)
    - Field inspection, observations
  - Non-destructive testing
    - (Class B,C)
    - Rebound number measurement, Schmidt hammer test
    - Ultrasonic pulse velocity

Rebound number measurement using Schmidt hardness tester

Approach for Assessment

- Semi-destructive testing
  - (Class D, E)
    - Color analysis on cores
    - Concrete, core, rubber, composite
    - Petrographic analysis
    - Drilling resistance
- Simplified analysis approaches (Class D, E)
  - Peak cross-sectional temperatures
  - Modified room temperature equations
  - Straightforward to apply
- Advanced analysis approaches (Class D, E)
  - FEM based numerical modeling
  - Realistic material properties of concrete and rebar
  - Accurate for cooling phase, deflections
  - Require significant computational effort

Approach for Assessment

- Three Stage Approach
  - Stage 1: Evaluate room temp. capacity
  - Stage 2: Evaluate response during fire exposure
  - Stage 3: Evaluate residual capacity after cool down
- Advanced Analysis Approach
  - Quite complex
  - FEM based numerical model
    - Coupled thermal & structural analysis
    - Failure based on both strength limit state
    - Material & geometric nonlinearity
- Accounts for effect of:
  - Realistic fire exposure (cooling phase)
  - Load level & restraint conditions
  - Distinct temp. dependent mat. properties
  - Strain hardening in reinforcement (tension softening in concrete at high temp).
  - Bond, spalling, creep etc.
  - Residual deformations
  - Member/system level

Advanced Analysis Approach for Evaluating Residual Capacity of RC Structures

Different fire exposure scenarios that can be accounted for in the approach
Stage 1: Evaluate Room Temp. Capacity
- Apply loads to simulate realistic loading conditions at room temperature
- Room temperature mechanical properties of concrete and steel reinforcement are utilized
- Strength limit state generally governs
- Corresponds to the point at which flexural or shear capacity is exceeded
- Both tension stiffening in concrete and strain hardening in reinforcement are accounted for in analysis

Stage 2: Evaluate Response during Fire Exposure
- Conduct a sequentially coupled thermal stress analysis to evaluate response during fire event
- Thermal conductivity and specific heat of concrete and reinforcing steel
- Modulus of elasticity, yield strength, ultimate strength and strain at ultimate strength are also a function of temperature
- Distinct heating and cooling phase properties
- Strength limit state corresponding to exceedance of flexural or shear capacity
- Deflection increases significantly at high temperature
- Deflection or rate of deflection limit state is to be applied as a reliable performance index

Stage 3: Evaluate Residual Capacity after Cool down
- If the beam survives fire exposure, trace residual response via incremental loading to failure, accounting for residual deformations from Stage 2
- After cooling down of the beam, post fire residual properties of reinforcing steel and concrete are utilized
- After cool down, compressive strength of concrete reduces, & properties of rein. steel recover
- Failure - strength limit state governs

Material Properties for Analysis
- Stage 1
  > Realistic uniaxial stress-strain relationships for concrete and steel at room temperature are adopted
  > Compression hardening and tension stiffening in concrete
  > Strain hardening in reinforcing steel
  > Stage 2
  > Temperature dependent thermal and mechanical properties
  > Eurocode 2 and 3 provisions
  > Stage 3
  > Residual uniaxial compressive and tensile strength of concrete after assumed to be 10% less than the strength attained at the maximum temperature
  > The residual stress-strain relationship for reinforcing steel is calculated using degradation observed by Neville et al. (1996)

Approach for Modeling Residual Response
- Pre-fire service conditions
- Response during fire exposure, and cooling
- Post-fire residual capacity

Approach for Assessment
- Flow chart illustrating the three stages involved in residual capacity evaluation in fire-exposed RC members

Case Study
- Two identical concrete beams, designated as beams B1 and B2, were analyzed for residual capacity after exposure to fire scenarios with distinct heating & cooling phases using the proposed approach

Summary of test parameters used for case study

<table>
<thead>
<tr>
<th>Condition</th>
<th>Fire Exposure</th>
<th>ACI Design Capacity (kN)</th>
<th>Residual Cycles of Fatigue Resistance (10^6)</th>
<th>Ultimate Residual Strain (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>50°C</td>
<td>157</td>
<td>150</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>2°C</td>
<td>135</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
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</tbody>
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Approach for Assessment
- Application of Advanced Analysis Approach
The three stage approach is implemented using the commercial FEA package ABAQUS.

- Discretization
  - Concrete discretized using 8 node linear brick elements (DC3D8 heat transfer elements or C3D8 stress elements with Reduced Integration)
  - Reinforcement discretized using 2 node link elements (DC1D2 heat transfer element or T3D2 truss element)
  - Perfect bond assumed between reinforcement and concrete and implemented through tie constraint

### Stage 1: Evaluating Room Temp. Capacity

<table>
<thead>
<tr>
<th>Beam designation</th>
<th>Beam reinforcement</th>
<th>Flexural reinforcement</th>
<th>Room temperature capacity: kN</th>
<th>Fire resistance (ACI 216) min</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>125X250</td>
<td>2 @ 12 mm</td>
<td>745</td>
<td>88.7</td>
</tr>
<tr>
<td>B2</td>
<td>180X300</td>
<td>2 @ 12 mm, 3 @ 18 mm</td>
<td>143</td>
<td>166.0</td>
</tr>
<tr>
<td>B3</td>
<td>300X400</td>
<td>2 @ 12 mm, 3 @ 25 mm</td>
<td>351</td>
<td>403.5</td>
</tr>
</tbody>
</table>

- Key Observations
  - Design capacity: 145 kN; ACI 318 design equation: 91 kN
  - Difference due to tension stiffening in concrete and strain hardening in rebar ignored by ACI 318.
  - Sufficient ‘reserve’ capacity leading to enhanced fire resistance (and residual capacity).

### Stage 2: Evaluating Response During Fire

- Key Observations: Thermal response
  - Cross-sectional temperatures in both beams continue to increase even as fire temperatures decay, owing to high thermal inertia of concrete
  - Peak rebar temperatures in B1 and B2 are calculated to be 592°C and 575°C at 170 min and 240 min respectively, well after heating phase of fire exposure has ended

- Key Observations: Structural response
  - Both beams do not fail during fire exposure and mid-span deflections recover once the rebar and concrete temperatures revert back to ambient temperatures
  - Noticeable residual deformation is left over in the fire exposed beams and they do not revert back to their pre-fire configuration

### Stage 3: Residual Response after Cool Down

- Key Observations
  - Significant residual deformation occurs in both fire damaged beams, calculated to be 43 mm for beam B1 and 74 mm for beam B2 respectively
  - Both fire damaged beams exhibit three key phases in deflection progression i.e., linear response (marked as A-B), onset of yielding in steel reinforcement (marked as B-C), and plastic deformation until failure (marked as B-C)
  - Peak moment-carrying capacity in fire damaged beams B1 and B2 was calculated to be 180 kNm and 164 kNm respectively, greater than design capacity

### Critical Factors Governing Residual Capacity

- Structural parameters
  - Load Level
  - Boundary Conditions
  - Sectional Dimensions

- Fire exposure scenario
  - Varying heating and cooling phases based on compartment characteristics

- Load Level
  - Stress level before and during fire exposure

- Support Conditions
  - Level of axial restraint

Failure of an RC beam after fire test inside the furnace, showing flexural cracks.
Critical Factors Governing Residual Capacity

- Fire exposure scenario
  - Effect of four different parametric fire exposure scenarios (DF1, DF2, DF3 and DF4) studied
  - Varying heating and cooling phases based on compartment characteristics

Schematic representation of a typical fire compartment

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Critical Factors Governing Residual Capacity

- Load Level (During fire)
  - Three different load ratios of 30%, 40% and 60%
  - Larger load ratio leads to greater mid-span deflections during identical fire exposures
  - For load ratio 30%, reduction in capacity after fire exposure is 15%
  - Post-fire reduction in capacity is about 26% when load ratio is 40%
  - Larger level leads to greater residual deformations and lower post-fire residual capacity

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Parametric Studies

- Fire exposure scenario
  - Beam BX1 fails under fire scenario DF1 due to excessive deformations
  - Higher rebar temperatures correspond with higher residual deformations
  - Higher residual deformations lead to a lower residual capacity in fire exposed RC beams
  - Fire exposure scenario has significant influence on residual capacity

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Summary

- RC structures, owing to their low thermal conductivity, high specific heat and slower degradation in concrete strength, experience minimal damage in most fires.
- Irreversible residual plastic deformations occur in RC members due to temp. induced damage sustained during fire exposure. These residual deformations are significantly larger than pre-fire (room temp.) deformations and can adversely affect post-fire serviceability of the fire damaged concrete members.
- Structures following fire exposure can be grouped under 5 classes. A range of techniques, ranging from reconnaissance to advance analysis, can be applied for undertaking post-fire damage assessment.
- Advanced analysis for evaluating residual capacity requires 3-stage of analysis: namely at pre-fire ambient conditions, during fire exposure, and following cooling of fire exposed member. The finite element computer software (ABAQUS) can be utilized for evaluating the response of fire exposed RC structures.
- Critical factors that influence post-fire residual capacity of RC members are fire intensity and duration of exposure, load level during fire exposure and the level of axial restraint. Of these, the most critical factors are temp. attained during fire (in rebar), as well as load level during fire exposure.
- Following a fire incident, fire damaged concrete members may satisfy design limit state from strength consideration, but need to be retrofitted to provide comparable level of safety (capacity) which existed prior to the fire incident.

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