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

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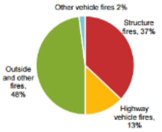
Outline

- 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

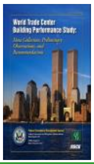
Background

Fire – Severe Hazard & Threat

- Fires cause thousands of deaths & billions of $$ of damage yearly
- 2017 Data – Fire Losses in USA (NFPA)
  - 1,319,500 fire incidents (1.7% decrease over 2016)
  - 3400 fire deaths (one every 154 min), 14,650 injuries (one every 36 mi
  - $23 billion direct property losses (includes $10 billion loss in Northern
  - Total loss > $50 billion (Estimate for fire losses in 2017)
  - 33% of fires in Structures - Residential fires being the most significant
- 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 – Compartmentation, Fire resistance
- Structural Damage/Collapse
  - Only limited number of fires grow in to full size fires
  - Structural collapse is very low; 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!



Fires by type occupancy, based on annual average fires between 2010-2014



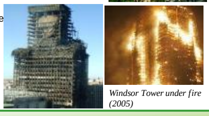
Background

Major Fires in High-rise Structures

- Notre-Dame Cathedral Fire, France (April 15, 2019 6:30 pm)
  - Masonry (walls and arches) with long-wooden truss (roof)
  - Roof collapse, structural damage
- Plasco building, Tehran, Iran (Jan, 2017)
  - Steel building, 17 Story
  - Complete collapse within few hours of fire exposure
- Grenfell Tower, London, UK; June 13, 2017
  - 24-storey, concrete building, 120 apts (600 people)
  - Constructed in 1974 (major renovation in 2016)
  - 1 staircase, No sprinklers, Alarms not activated
  - Short circuit in Faulty fridge??
  - Ignition of exterior cladding - façade??
  - 79 deaths, 86 injuries
- TU Delft, Faculty of Architecture building, NL (2008)
  - RC building, 13 Story
  - Cause: electric short-circuit in coffee vending machine - 5th floor
  - Flashover within 40 minutes of ignition
  - Resulted in partial collapse of the north section
- Windsor Tower, Madrid (2005)
  - 32 story tower; 29 floors above & 3 below ground; NSC
  - 1st 16 floors made of concrete; steel perimeter columns above
  - Fire started at 21st floor & spread quickly
  - Downward spread due to falling of burning debris
  - Remained standing after a 26 hour multi-floor fire
- World Trade Center Buildings, New York (2001)
  - Impact followed by fire
  - 9 collapsed, 18 damaged (Mostly due to fire)
  - Significant structural damage; fire protection systems compromised before fire

Plasco building collpase (2017)

TU Delft Faculty of Architecture building under fire (2008)



Windsor Tower under fire (2005)

Background

Grenfell Tower, June 13, 2017

- Fire occurred on June 13 2017 at 12:54 am
  - 79 deaths, 86 injuries
  - Fire burned for 8-9 hours
  - Over 200 firefighters and 40 fire engines
- Building features: 24-storey concrete building
  - Located at North Kensington, London, UK
  - Constructed in 1974 (renovations in 2016)
  - 120 apartments (600 people)
- Fire cause/spread
  - Short circuit - faulty fridge/central gas system
  - Ignition of exterior cladding - façade??
    - Polyester powder-coated aluminum composite panels - Cheap, aesthetics; combustible
    - Rapid fire spread in 60 min (2-24 story)
- Buildings problems
  - Designed with **one** emergency stair
  - Lack of proper ventilation system
  - Many fire code violations - worries on fire safety
    - No sprinklers, Alarms were not activated
    - Firefighting equipment not checked for 4 Y
    - Warnings of fire risk - dismissed by owner
- Lessons learned
  - Fire spread/control (compartmentation)
  - Occupants asked to "Stay-where-you-are"
  - Enforcing fire regulations - timely
- Building - demolished

Background

Major Fires in Structures - Bridges

Major fires in bridges over last two decades in the US

- 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 350 feet of the span suffered complete collapse 1 hour into fire
  - Damage to adjacent spans
- Macarthur Maze fire California, US (2007)
  - Steel girder bridge
  - Fuel tanker with 8,600 gallon of fuel collided with guard rail
  - Collapse in 17 minutes into fire
- Puyallup bridge fire, WA, US (2002)
  - Pre-stressed concrete girder bridge
  - Caused by railroad tanker carrying 30,000 gallons of Methyl Alcohol
  - Fire lasted for almost two hours
  - Bridge re-opened the next day
- Rapid damage assessment is much more critical

Interstate 85 fire, (Atlanta, 2017)

Puyallup bridge fire and damage (Washington, 2002)

MacArthur Maze collapse fire and collapase (California, 2007)

I-85 Bridge collapse, Mar. 30th 2017

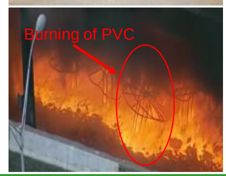
Background

- 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.

I-85 Bridge collapse, Mar. 30th 2017

Background

- Both northbound and southbound bridges of I-85 needed to be replaced
  - 100 ft of span (girders + deck) collapsed
  - 3 sections damaged (significant spalling in piers)
- Spalling of concrete lead to firefighters leave the scene
- Spalling – main cause of collapse

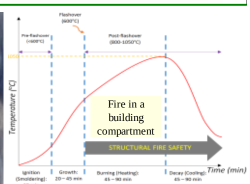


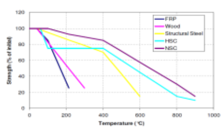
Concrete Structures under Fire

Fire Resistance Design

- **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 steel)**
    - **High Specific Heat (< 2×C_{steel})**
    - **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!**

The Park Central under fire, Venezuela, 2004





Typical rates of temperature induced strength degradation for different construction materials

Fire Performance of Concrete Structures

Fire Resistance Design

90 West Street (23 story, RC bldg, 1907) set on fire due to falling debris from collapse of the Twin Towers on 9/11

No collapse (Reinstated in 2005) Uncontrolled 'firestorm' for 5 days Prescriptive fire rating 2 hour

In contrast…

7 World Trade Center (47 Story, Steel bldg, 1987) on fire after the collapse of the Twin Towers on 9/11

Collapsed completely in 8 hours Prescriptive fire rating 3 hour

Significant residual capacity can be retained **in a structure** following a fire event, **especially in case of RC construction**!

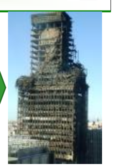
Need for Evaluating Residual Capacity

Fire Resistance Design

Most **fires** do **not cause collapse**, especially **concrete structures**. **Significant residual capacity exists**, which needs to be assessed!

- **Post-fire occupancy and safety**
  - **Extent of residual capacity** depends on number of **interdependent factors**
  - Ensure **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

Windsor Tower (32 Story, RC+Steel, 1979); Stood for **6 months** before being demolished

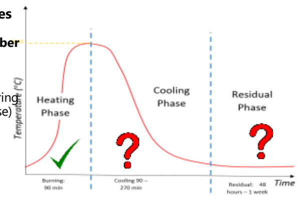


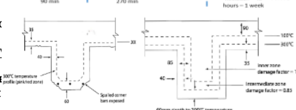
Parking structure collapse after 24 hours of cool down with fire fighters still inside, Sweden, 2004

State-of-the-Art: Residual Capacity

Knowledge Gaps

- **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
- **Current Guidelines and Provisions**
  - Assessment, Design & Repair of Fire-damaged Concrete Structures, The Concrete Society, 2007 (UK)
  - Fire Protection Planning Report, Portland Cement Association, 1994 (US)
  - 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**





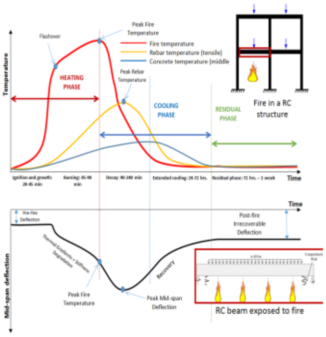
Fire damage assessment and residual capacity based on current guidelines (The Concrete Society, 2007)

Modeling Residual Response

Knowledge Gaps

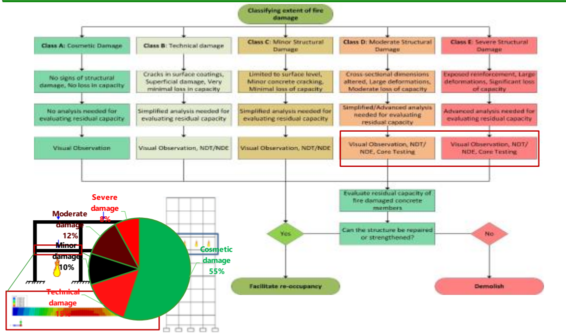
- **RC Building under Fire**
  - Complete building does **not burn simultaneously**
  - **Limited compartments (floors)** are **subject to fire** at any given time
- **Modeling complexities**
  - Experience large thermal gradients across depth
  - Distinct material properties during heating and cooling
  - Thermal cond., compressive strength, Load Induced Thermal Strain (LITS) are irrecoverable
  - Temp. induced degradation in tensile and bond strength
  - Residual thermal & shrinkage strain& deformations
- **Uncertainty in post-fire response**
  - Variability in **fire exposure scenario**
  - **Load level; Material models, BC's**
- **Advance Analysis Approaches**

Both **temp. history, accumulated material/ structural damage, as well as conditions** present during fire exposure, **influence residual capacity** of fire exposed RC members



Fire Damage Assessment Procedure: General Overview

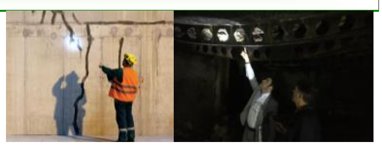
Approach for Assessment



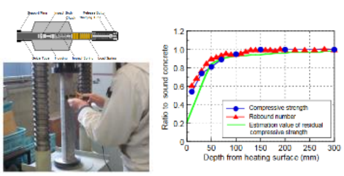
Fire Damage Assessment: Reconnaissance to Advanced Analysis

Approach for Assessment

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



Visual inspection of fire damaged structures

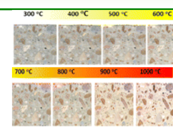


Rebound number measurement using Equotip hardness tester

Fire Damage Assessment: Reconnaissance to Advanced Analysis

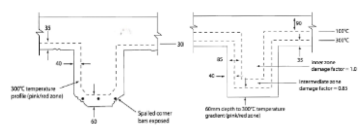
Approach for Assessment

- Semi-destructive testing (Class D, E)
  - Color analysis on cores
    - ✓ Concrete cores, reibar coupons
  - 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)
  - FE based numerical modeling
  - Realistic material properties of concrete and rebar
  - Account for cooling phase, post-fire residual deflections
  - Require significant computational effort



Color change in siliceous aggregate concrete

Localized evaluation of the damage using drill probes

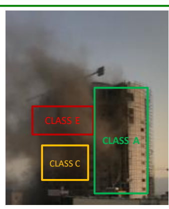


Fire damage assessment and residual capacity based on current guidelines (The Concrete Society, 2007)

Case study: Hotel Aseman Fire, Iran

Approach for Assessment

- **Building features:**
  - 22-storey
  - 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



Class A damage to unexposed regions

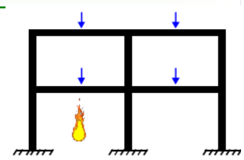
Class E damage to floor slabs

Class C damage in shear wall

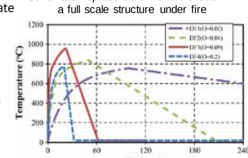
Advanced Analysis Approach for Evaluating Residual Capacity of RC Structures

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 stiffening in concrete at high temp.
  - Bond, spalling, creep etc.
  - Residual deformations
  - Member/system level



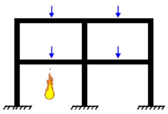
Schematic representation of a RC beam in a full scale structure under fire



Different fire exposure scenarios that can be accounted for in the approach

Approach for Modeling Residual Response

Approach for Assessment



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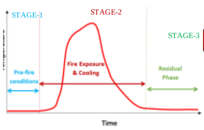
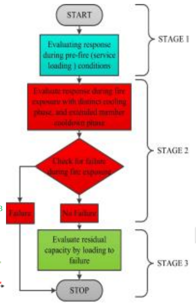
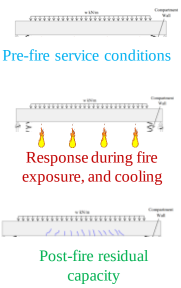
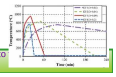








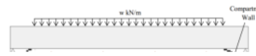
Flow chart illustrating the three stages involved in residual capacity evaluation in fire exposed RC members

Kodur V.K.R., Agrawal A. 2016, An approach for evaluating residual capacity of reinforced concrete beams exposed to ... Structures, 110, 293-306

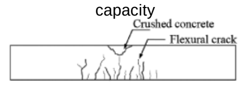
Stage 1: Evaluate Room Temp. Capacity

Approach for Assessment

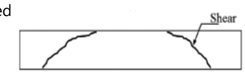
- **STAGE 1: Analysis at room temperat**
  - Apply loads to simulate realistic loading conditions at room temperature
  - Room temperature mechanical properties of concrete and steel reinforcement are utilized
  - Strength limit state generally governs
  - Corresponds to the point at which flexural or shear capacity is exceeded
  - Both tension stiffening in concrete and strain hardening in reinforcement are accounted for in analysis



Stage 1: Room temperature capacity



Flexural failure

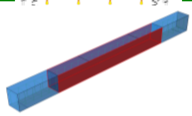


Shear failure

Stage 2: Evaluate Response during Fire Exposure

Approach for Assessment

- **STAGE 2: Analysis 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



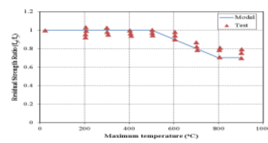
Failure limit states during fire exposure

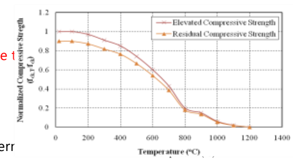
- **Thermal Limit State** (ASTM E119)
  - Limit of unexposed temperature
    - Average of 9 points = 140°C or at any point = 180°C
  - Limit of rebar temperature: 593°C
- **Strength Limit State** (ASTM E119)
  - Moment or shear capacity exceeds external loads
- **Deflection Limit State** (BS 476)
  - Maximum deflection limit: L/20
  - Rate of deflection limit: $L^2/9000d$(mm/min) or L/30

Stage 3: Evaluate Residual Capacity after Cool down

Approach for Assessment

- **STAGE 3: Analysis after fire exposure**
  - If the beam survives fire exposure, trace residual response via incremental loading to failure, accounting for residual deformatio from Stage 2
  - After cooling down of the beam, post fire residual properties of reinforcing steel and concrete are t be utilized
  - After cool down, compressive strength of concrete reduces, & properties of reinf. steel recover
  - Failure - strength limit state goverr





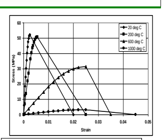
Normalized compressive strength of concrete with maximum exposure temperature

Material Properties for Analysis

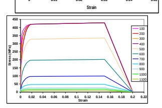
Approach for Assessment

- **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 Neves et al. (1996)

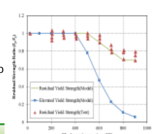
Stress-strain curves for concrete in compression at el. temp. as per EC 2



Stress-strain curves for reinforcing steel at el. temp. as per EC 2



Residual yield strength for reinforcing steel after exposure to el. temp.



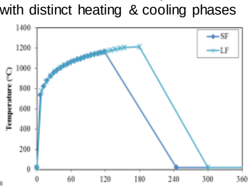
Application of Advanced Analysis Approach

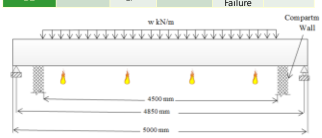
Case Study

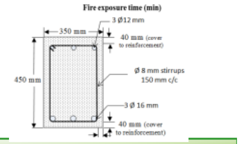
Two identical concrete beams, designated as beams B1 and B2, were analyzed for residual capacity after exposure to fire scenarios with distinct heating & cooling phases using the proposed approach

Summary of test parameters used for case study

Beam designation	Support Condition	Fire exposure	ACI design capacity (kN-m)	Predicted fire resistance (min)	Predicted residual capacity (kN-m)
B1	Simply supported	SF*	191	No Failure	189
B2		LF**		No Failure	164





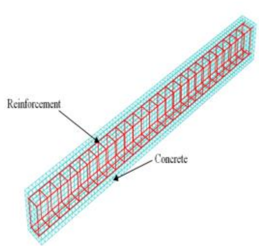


Finite Element Model

Case Study

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**

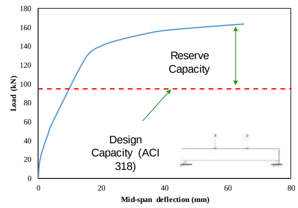


Discretized view of the selected beam for numerical simulation

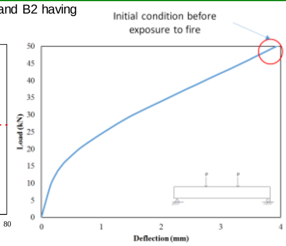
Stage 1: Evaluating Room Temp. Capacity

Case Study

Evaluation of room temperature capacity of B1 and B2 having identical dimensions and reinforcement details



Complete load-deflection response at room temperature

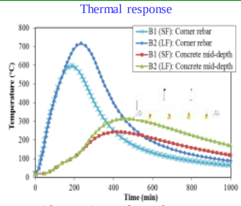


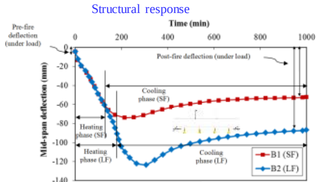
Load deflection response at room temperature (Stage 1) prior to fire exposure (Stage 2)

- **Key Observations**
  - Predicted capacity by FE model: 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)

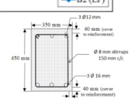
Stage 2: Evaluating Response During Fire

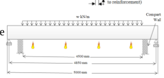
Case Study





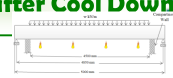
- **Key Observations -Thermal response**
  - Cross-sectional temperatures in both beams continue to increase even as fire temperatures decay, owing to high thermal inertia of concrete
  - Peak rebar temperatures in B1 and B2 are calculated to be 592°C and 715°C at 170 min and 240 min respectively, well 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





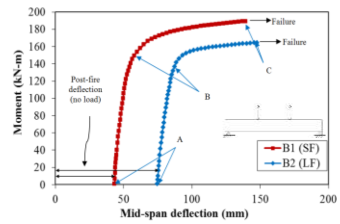
Stage 3: Residual Response after Cool Down

Case Study



Predicted post-fire response of fire damaged beams B1 and B2

- **Key Observations**
  - Significant residual deformation occur 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 in), and plastic deformation until failure (marked as B-C)
  - Peak moment-carrying capacity in fire damaged beams B1 and B2 was calculated to be 189 kN-m and 164 kN-m respectively, greater than design capacity



Predicted residual moment-deflection response for fire damaged beams

Critical Factors Governing Residual Capacity

Parametric Studies

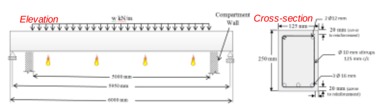
- **Structural parameters**
  - Load Level
  - Boundary Conditions
  - Sectional Dimensions
- **Fire exposure scenario**
  - Varying heating and cooling phases based on compartment characteristics
- **Load Level**
  - **Stress level** before and during fire **exposure**
- **Support Conditions**
  - Level of **axial restraint**

Failure of an RC beam after fire test inside the furnace, showing flexural cracks

Critical Factors Governing Residual Capacity

Parametric Studies

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



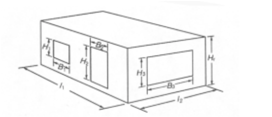
Dimensions, loading and reinforcement details of beam BX1 selected for parametric study

Beam designation	Beam dimensions: mm	Flexural reinforcement		Room temperature capacity: kN		Fire resistance (ACI 216): min
		Top bars	Bottom bars	ACI 318	Model	
BX1	125X250	2 ø 12 mm	3 ø 16 mm	74.6	89.7	60
BX2	180X300	2 ø 12 mm	3 ø 20 mm	143	168.8	120
BX3	300X480	2 ø 12 mm	3 ø 25 mm	351	403.5	120

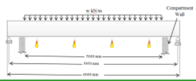
Critical Factors Governing Residual Capacity

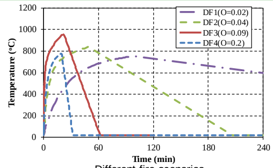
Parametric Studies

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

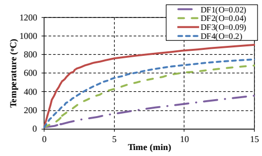


Schematic representation of a typical fire compartment





Different fire scenarios

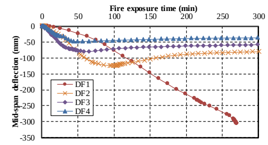


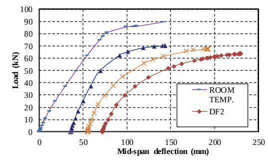
Zoomed in fire scenarios (First 15 minutes)

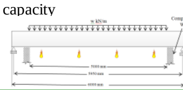
Critical Factors Governing Residual Capacity

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



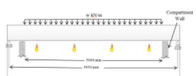


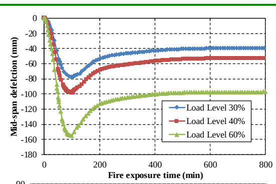


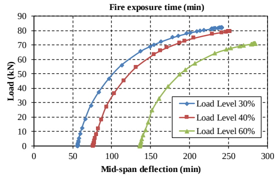
Critical Factors Governing Residual Capacity

Parametric Studies

- **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 **60%**
  - Larger level leads to greater residual deformations and lower post-fire residual capacity







Summary

- **RC structures**, owing to their **low thermal conductivity**, **high specific heat** and **slower degradation in concrete strength**, experience **minimal damage** in **most fires**.
- **Irrecoverable 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 member.
- **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**.

Acknowledgements

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- **Michigan State University**

Thank You

Questions