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SPECIAL MOBILITY STRAND

DAMAGES OF REINFORCED CONCRETE STRUCTURES CAUSED BY FIRE AND POSSIBILITIES FOR THEIR REPAIR

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AUTHORS: Mirjana MALEŠEV & Vlastimir RADONJANIN PRESENTER: Mirjana MALEŠEV

> University of Novi Sad, Faculty of Technical Sciences Department of Civil Engineering and Geodesy - Novi Sad - Serbia

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LECTURES TOPICS

- Behaviour of concrete and reinforcement under elevated temperature and characteristic damages of RC elements caused by fire.
- Methods for repair of damaged RC elements after fire attack and Case study: Assessment and repair of high rise building after the fire











BEHAVIOUR OF CONCRETE AND REINFORCEMENT UNDER ELEVATED TEMPERATURE CAUSED BY FIRE

AUTHORS: Mirjana MALEŠEV Vlastimir RADONJANIN

PRESENTER: Mirjana MALEŠEV







OUTLINE

- Introduction
- Fundamentals of concrete composition and structure
- Damage mechanisms of concrete and reinforcing steel under elevated temperature
- Types of damages of reinforced concrete due to fires and their classification
- Upgrading the knowledge













- From the beginning of the 21st century, every year 7 8 million fires occur in the world......(13 fires /min)
- Every year more than 80.000 people die in fires worldwide.

Country	Population inhab. mill	Nº	of fires	N° of fire deaths	Nº of per 1(inhab	fires 000	N° of fire deaths pe 100.000 II	r nhab.
USA	321	W	1,345,000	3.250		4.1		1,0
Russia	146		145,000	9,405		1.0		6,4
Netherlands	17	EU	125,000	81		7.4		0,5
Sweden	9 <i>,</i> 85		22,785	110		2,3		1,1
Serbia	7.2		16,805	73		2,3		1,0

Indicators in 2015*

*CTIF - International Association of Fire and Rescue Services CTIF reports No 21, 2016 & No 22, 2017 "World fire statistics"







Distribution of fires by types (2015)







Conclusion:

Structure fires have the largest participation of 38.2% (>2.7mill).



INTRODUCTION





Basics building elements:

- Load bearing structure,
- Envelope,
- Partitions and
- Installations.

Each: Affected Contribute Damaged







INTRODUCTION







Load bearing structures are made of:

- Concrete (plane, reinforced, prestressed),
- Metal (steel, aluminium),
- Timber (traditional, glulam, PSL, LVL...),

Masonry (stone, clay& concrete bricks & blocks). incombustible

incombustible incombustible combustible



Since RC concrete structures are the most common, they will be the topic of our lectures.



INTRODUCTION





Reinforced concrete is considered a material that shows an acceptable resistance to high temperatures due to the following properties:

- incombustibility,
- small thermal conductivity,
- small strains at rising temperatures,
- large dimensions of element cross section.

Therefore, the inner part of RC elements remains intact and continues to transmit load.

Concrete structures completely demolished by fire are rare in the practice, and

most of the facilities with RC structure have been successfully repaired and used again, even those which have been exposed to great fires.







INTRODUCTION





A fundamental of concrete composition and structure

For realistic assessment of the structure after a fire it is necessary:

- to know the behaviour of concrete and reinforcing steel at high temperature,
- to be able to recognize the type and degree of damage due to the fire and
- to separate them from similar damages that result from other causes.

DEFINITIONS

Concrete is a composite material containing random pieces over a wide range of length scales, from nanometres to centimetres.

Concrete is a highly heterogeneous and complex material brittle in tension and relatively tough in compression.







A fundamental of concrete composition and structure

Concrete is a composite material that consists mainly of mineral aggregates bound by a matrix of hydrated cement paste

Hardened concrete





CONCRETE COMPOSITION





A fundamental of concrete composition and structure



Answer:

- Water always participates in chemical reaction – chemically bonded water.
- Physically bonded water is entrapped in gel pores.
- The hydrated cement paste is capillary porous and contains a relatively large amount of free water







DAMAGE MECHANISMS OF CONCRETE AND REINFORCING STEEL UNDER ELEVATED TEMPERATURE

When is subjected to heat concrete undergoes various chemical and physical changes.

The main changes occur primarily in the hardened cement paste, and the main cause is water in hardened cement paste (chemicaly and physicaly bounded and especially free water)

Changes in hardened cement paste

Physical pro	cesses	Chemical transformations		
~100°C	evaporation of free water	50°C-110°C decomposition of ettringite		
100°C-400°C	loss of physically bonded water	450°C-550°C endothermic dehydration of calcium hydroxide		
>400°C	chemically bonded water will be lost	600°C-700°C decomposition of C-S-H gel		
>1200°C	melting of hardened cement paste			
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Changes in aggregate

Type of agg.	Siliceous	Carbonate	LWA	
300°C-350°C	r IIA	nineral types of aggregate a	re stable	
400°C-650°C	Change in crystal structure of qartz	Stable	Stable	
600°C-900°C		Decarbonation (CaO+CO ₂)	Depend on type of LWA	
>1100°C	Some types of aggregate begin to melt			

Changes of mechanical properties of concrete during and after fire

Reduction factor for concrete		Temperature (°C)						
		<100	100	200	300	400	500	600
Compressive	During heating	1.00	0.90	0.85	0.85	0.80	0.65	0.45
strength	After cooling	1.00	1.00	1.00	0.90	0.80	0.60	0.40
Tensile strength	During heating and after cooling	1	0.75	0.50	0.25	0	0	0
Modulus of	During heating	1	0.90	0.75	0.50	0.40	0.25	0.15
elasticity	After cooling	1	0.90	0.80	0.70	0.55	0.30	0.15









Changes in colour



Reinforcing steel is much more sensitive to high temperatures than concrete.

200°C-300°C	Steel with carbon	"blue brittless"
200°C-400°C	Prestressing wires & strands	Considerable loss of strength
>450°C	Cold worked steel	Loss of residual strength
>600°C	Hot rolled steel	Loss of residual strength





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DAMAGE MECHANISMS...





THERMAL SPALLING

Definition:

Violent or non-violent breaking off of layers or fragments of concrete from the surface of a structural element during or after it is exposed to high and rapidly rising temperatures.

Causes:

- Pore pressure rises due to evaporating water when the temperature rises;
- Compression of the heated surface due to a thermal gradient in the cross section;
- Internal cracking due to difference in thermal expansion between aggregate and cement paste;
- Strength loss due to chemical transitions during heating.









All of these theories are based on the phenomena of "the movement of heat and / or movement of moisture" that cause stresses.

Unfortunately, mentioned theories have not been entirely confirmed by a number of experiments.

The same conclusion can be derived for numerical modelling that attempt to explain and predict the occurrence of spalling









TYPES OF THERMAL SPALLING

Type of spalling	Appereance	Description
Explosive spalling	In the first 30min	Violent breaking off of concrete fragments at high rise temperatures
Surface spalling	In the first 30min	Violent separation of small or larger pieces of concrete from the cross section at high temperatures - (popping off)
Aggregate spalling	In the first 90min	Splitting of aggregates due to their decomposition or changes at high temperatures
Corner spalling	In the first 90min	Removal of concrete cover from corners at high temperature due to the temperature impact from two sides
Sloughing off spalling	After longer exposure to fire	Non-violent breaking off of concrete fragments after longer exposure to high temperatures, when concrete loses its strength
Post-cooling spalling	After fire, during cooling	Non-violent breaking off of concrete fragments during cooling - (concrete with calcerous aggr.)









TYPES OF THERMAL SPALLING





BASIC VISIBLE DAMAGES OF RC





EXPLOSIVE SPALLING

Explosive spalling occurs:

- rapid temperature rise > 30°C/min
- concrete reaches 150-250°C
- moisture in the concrete is heated faster than it can migrate
- Explosive spalling is caused by two processes:

thermo-mechanical

the stress originates from thermal deformation within the concrete due to thermal gradients

thermo-hydral

due to the build-up of gas pressure fields in the porous network



Influencing factors are:

- permeability
- saturation level (OPC 3%, HPC 2,5%)
- section shape and size
- heating rate and profile







CRACKING

occurs due to exceeding of concrete tensile strength. Causes:

- Shrinkage of hardened cement paste due to drying at high temp.;
- Temperature gradient that induces high tensile stresses between heated surface layer and colder inner zone of concrete
- Difference in thermal expansion between concrete and rebars;

TYPES OF CRACKING











REINFORCEMENT DAMAGES

occur due to loss of strength and ductility of steel.

Characteristic visible fire damages:

- Plastic deformations due to restrained elongation;
- Breaking of bars due to loss of ductility or local reduction of bar cross section because of melting of steel.





BASIC VISIBLE DAMAGES OF RC





CLASSIFICATION OF DAMAGES

This classification is proposed by Ingham & Tarada and modified in relation to the degree of affected part of RC element cross section.

It has five damage degrees (0, 1 - 4)

"0" is sign for undamaged RC element











Damage degree	Affected part of cr./sect.	Illustration	Features observed
2	Concrete cover	A contraction of the contraction	Moderate crazing - mesh like cracks Surface spalling Agg. spalling Change of concrete colour (pink or red) Rebars are non- visible or localy visible at places with insufficient cover (<25%)







Damage degree	Affected part of cr./sect.	Illustration	Features observed
3	Concrete matrix	Cover Matrix	Extensive crazing Corner spalling and cracks along rebars Sloughing off sp. Change of concrete colour (pink/red/whitish grey) < 50% of rebars are visible Loss of concrete strength Minor deflection of RC elements







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degree of cr./sect. 4 Concrete core Orege Orege Matrix Orege Matrix Orege Matrix Orege Matrix Orege Orege Orege Concrete core Orege Orege Orege <th>Damage</th> <th>Affected part</th> <th>Illustration</th> <th>Features observed</th>	Damage	Affected part	Illustration	Features observed
4 Concrete core concrete colour: whitish grey/buff Possible melting of concrete Inner delamination of concrete Inner delamination of concrete Inner delamination delaminat	degree	of cr./sect.		
	4	Concrete	Core National Antional Antiona	Deep extensive spalling > 50% of rebars are visible Change of concrete colour: whitish grey/buff Possible melting of concrete Inner delamination of concrete Impaired bond between concrete and rebars Possible buckling and breaking off of rebars







VULNERABILITY OF CONCRETE STRUCTURES DUE TO FIRE







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VULERABILITY OF RC...





MEMBER ANALYSIS – Type of concrete LIGHT WEIGHT CONCRETE (LWAC/LWC)

Structural lightweight concrete with artificial mineral aggregate



Expanded clay

LWAC <=> NWC

ADVANTAGES

- Lower thermal conductivity
- Slower heat transmission
- Higher residual strength
- Less prone to crack
- Smaller deterioration due to elevated temperature
- Better rebar protection
- Better preservation of bearing capacity

DISADVANTAGES

- Higher reduction of tensile strength
- Increasing of spalling occurence above 350°C







MEMBER ANALYSIS – Type of concrete **:HIGH STRENGTH CONCRETE (HSC)**

Large-scale constructions: tall buildings, bridges, tunnels...

Basic properties: high compressive strength & modulus of elasticity, decreased permeability ...

HSC <=> NWC

DISADVANTAGES

- Higher great risk to explossive spalling
 - Earlier occurence
 - More prone to spall at concrete moisture $\geq 2,5\%$
 - Less critical distance (5-10cm comp.to 20-40cm in OC)
 - Considerable depth in total
- Significant reduction of compressive strength
 - Earlier decrease of compressive strength (at 150°C up to 30%)
 - Redistribution of internal sresses (due to weakness of cement matrix)





OC





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MEMBER ANALYSIS – Type of concrete FIBER REINFORCED CONCRETE (FRC)

Definition: FRC contains short discrete fibers that are uniformly

distributed and randomly oriented.



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MEMBER ANALYSIS – Construction details

Shape & dimensions of cross section:



Smaller dimensions of cross section = smaller unheated inner part = larger damaged part of concrete.

Progressive heat penetration







MEMBER ANALYSIS – Construction details

Position of member:



Progressive heat penetration Most intesive spalling









MEMBER ANALYSIS – Construction details

Shape & dimensions of cross section:



Arragement of reinforcement



Progressive heat penetration Most intesive spalling Rebars with larger diameter and inadequate layout contribute to the intensification of damages



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MEMBER ANALYSIS –

Construction and architectural details

Placement of electrical & similar installations within crosssection of RC members



Local deep overheating of concrete Local damage of concrete core Deformed rebars



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MEMBER ANALYSIS – Constr. & arch. details

 Holes for penetration of installations



 Presence of defects, previous damages & repairs



- Concrete honeycomb
- Segregation zones
- Bad cold joints
- Thin cover...

Inadequate sealing of holes=Faster & direct fire spreading

Local deep overheating of concr. Serious spalling



VULERABILITY OF RC...





MEMBER ANALYSIS – Architectural details

Existence and nature of protective and decorative layers

incombustible



Incombustible finishing layers have protecting role during the fire. mortar, plasterboard, ceramic and stone tiles

Combustible finishing layers contribute to local development of high temperature on surface of RC members and intensify fire damages. wood, plastics, textiles,



VULERABILITY OF RC...







CONCLUSION

The authors of this paper, through brief theoretical consideration of damage mechanisms of concrete and steel, classification of fire damages of RC structures and possible repair methods with respect to affected part of cross-section, tried to assist engineers in practice to understand complex behaviour of reinforced concrete at elevated temperatures and to make decision about possible repair solution.

On the basis of the analysis of the vulnerability of structural elements at the material level, at the level of member and through the analysis of the entire load bearing structure, it is concluded RC structures in general have satisfactory fire resistance, but analysed influence factors, such as type of concrete, shape and dimensions of members, defects etc., could improve or jeopardise vulnerability of whole structure.









CONCLUSION

On the other hand, composite or prestressed structures are more sensitive when to elevated temperatures compared to RC structures.

When composite structures are designed or structural elements of different materials are combined, the vulnerability of the entire primary loadbearing structure depends on the vulnerability of the most sensitive structural member.

Therefore all elements of the primary structure must have the same degree of vulnerability, which is achieved by the adequate choice of the structural system, the material for the structural members and the active fire protection measures.









Thank you for your attention

miram @uns.ac.rs radonv@uns.ac.rs

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