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K-FORCE

SPECIAL MOBILITY STRAND

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

Tuzla, January 2019.

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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

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BEHAVIOUR OF CONCRETE AND REINFORCEMENT UNDER ELEVATED TEMPERATURE CAUSED BY FIRE

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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

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INTRODUCTION

- 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.

Indicators in 2015*

Country	Population inhab. mill	Nº of fires	Nº of fire deaths	Nº of fires per 1000 inhab.	Nº of fire deaths per 100.000 Inhab.
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	9,85	22,785	110	2,3	1,1
Serbia	7.2	16,805	73	2,3	1,0

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

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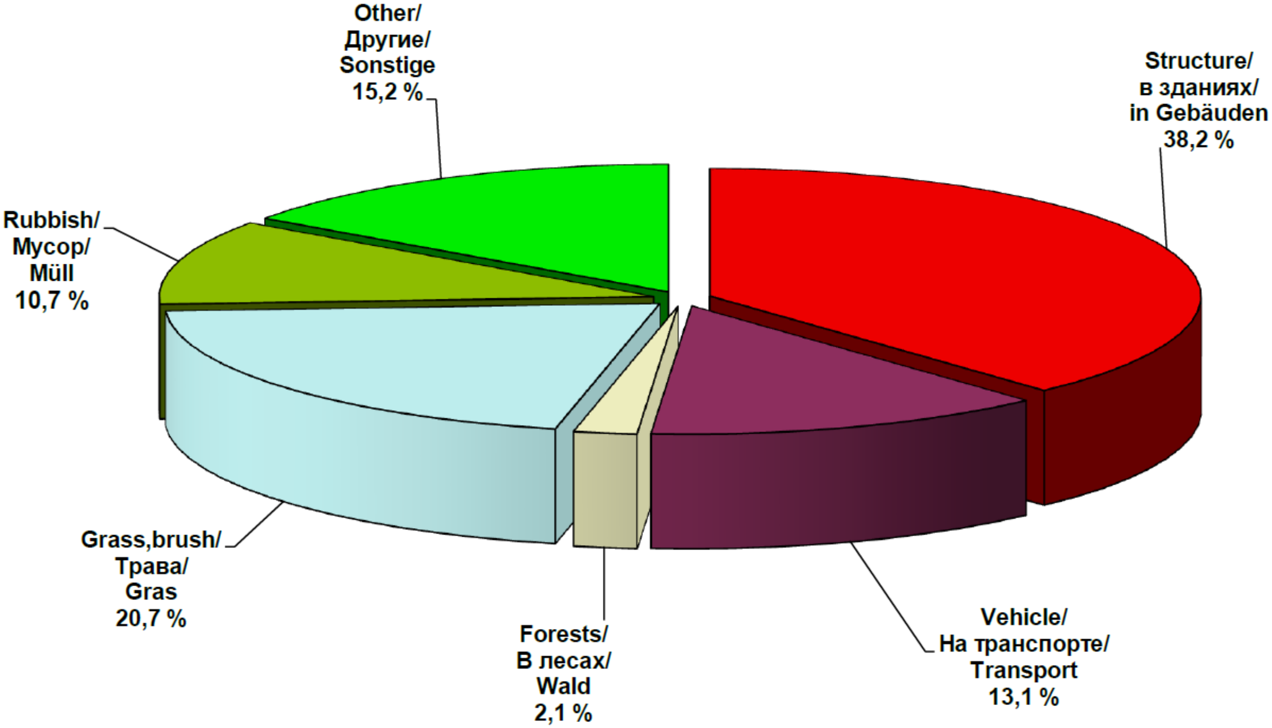
INTRODUCTION

Distribution of fires by types (2015)



Conclusion:

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

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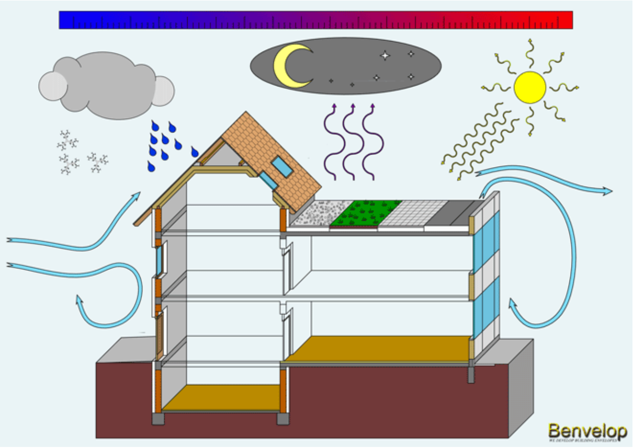
INTRODUCTION

Basics building elements:

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

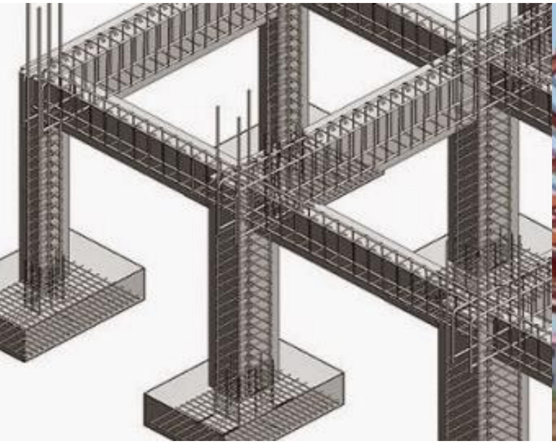
Each:
Affected
Contribute
Damaged



INTRODUCTION

Load bearing structures are made of:

❖ **Concrete** (plane**, reinforced,** prestressed),	incombustible
❖ Metal (steel, aluminium),	incombustible
❖ Timber (traditional, glulam, PSL, LVL...),	combustible
❖ Masonry (stone, clay& concrete bricks & blocks).	incombustible




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

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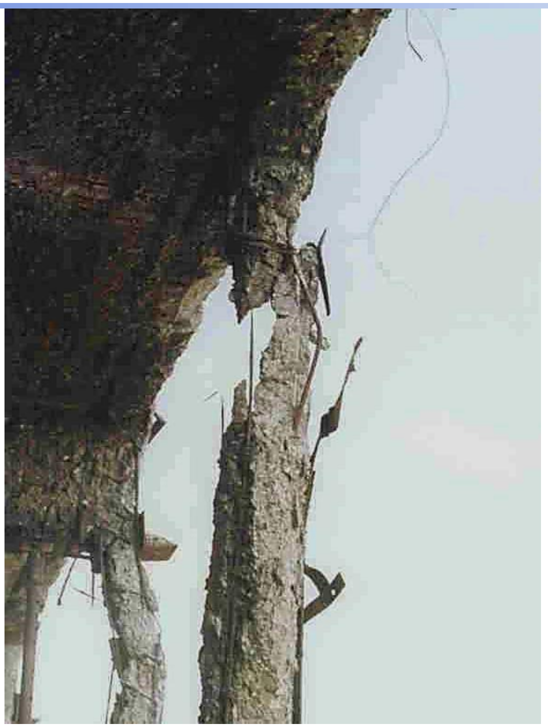
Reinforced concrete is considered a material that shows an acceptable resistance to high temperatures due to the following properties:

- 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.

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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.

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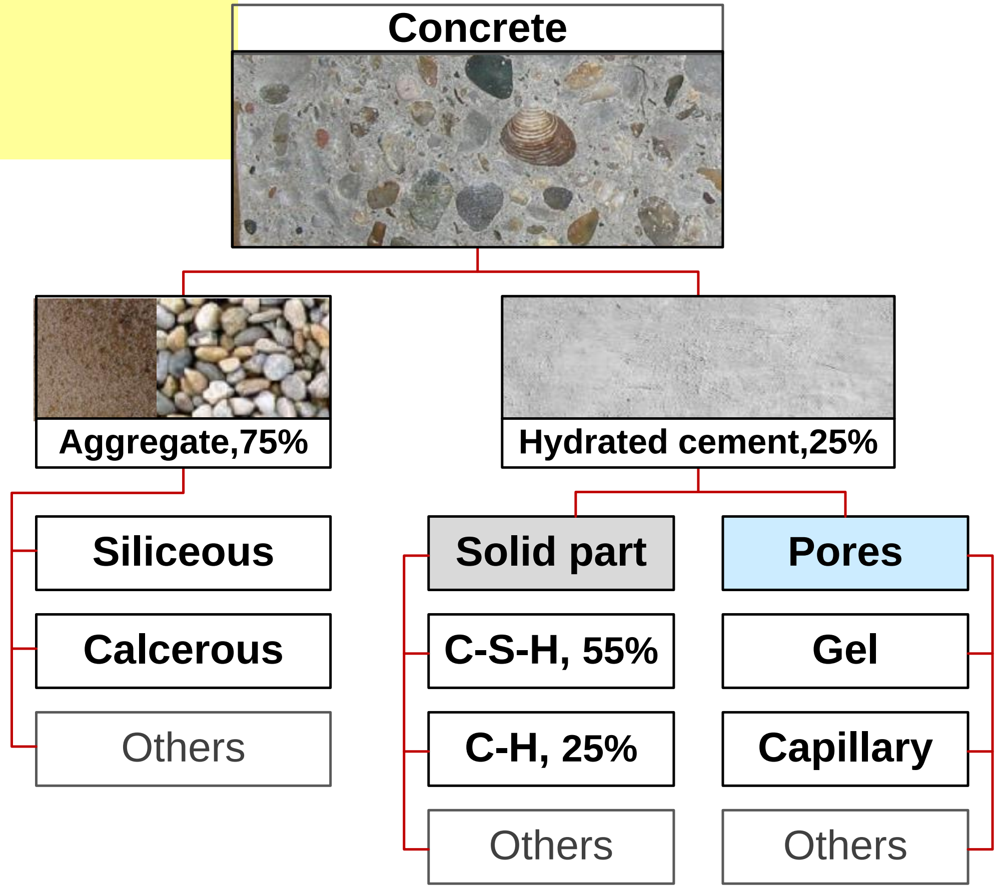
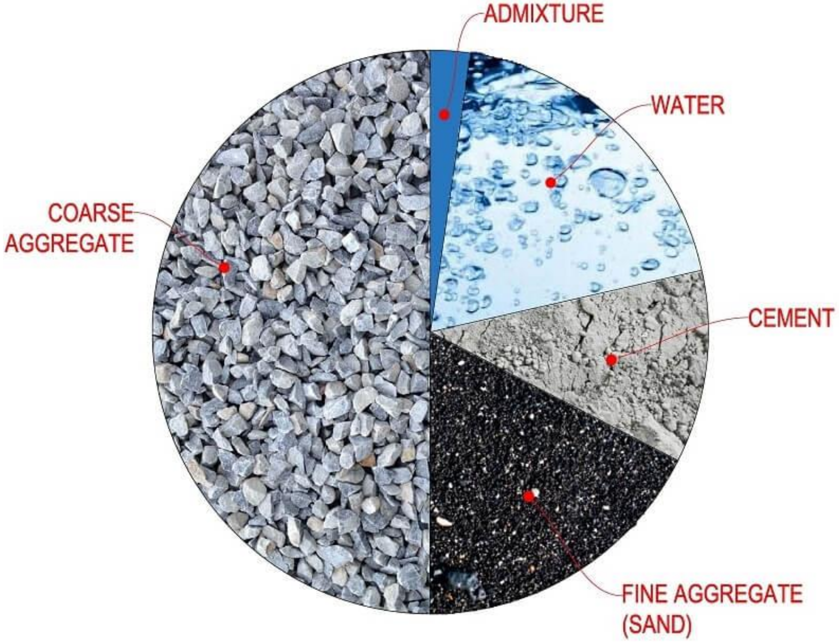
A fundamental of concrete composition and structure

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

Hardened concrete



Fresh concrete



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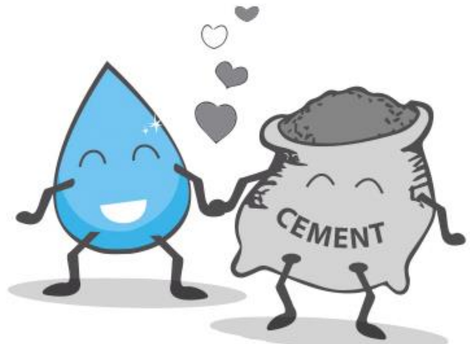
A fundamental of concrete composition and structure

Where is water?

Water, cca17%

- Solid
  - C-S-H, C-H → **Chemically bonded** → Very strong
- Pores
  - Gel → **Physically bonded** → Relatively strong
  - Capillary → **Free** → Weak bond



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

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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 processes		Chemical transformations	
~100^{0}C	evaporation of free water	50^{0}C-110^{0}C	decomposition of ettringite
100^{0}C-400^{0}C	loss of physically bonded water	450^{0}C-550^{0}C	endothermic dehydration of calcium hydroxide
>400^{0}C	chemically bonded water will be lost	600^{0}C-700^{0}C	decomposition of C-S-H gel
>1200^{0}C	melting of hardened cement paste		

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Changes in aggregate

Type of agg.	Siliceous	Carbonate	LWA
300^0C-350^0C	**All mineral types of aggregate are stable**		
400^0C-650^0C	Change in crystal structure of qartz	Stable	Stable
600^0C-900^0C		Decarbonation ($CaO+CO_2$)	Depend on type of LWA
$>1100^0C$	Some types of aggregate begin to melt		

Changes of mechanical properties of concrete during and after fire

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

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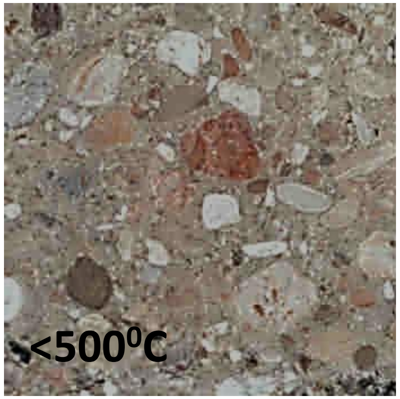
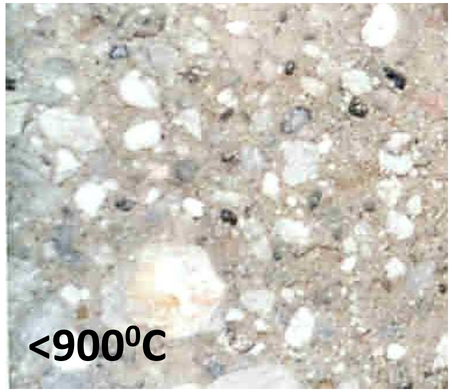
Changes in colour





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

200^{0}C-300^{0}C	Steel with carbon	„blue brittless“
200^{0}C-400^{0}C	**Prestressing wires & strands**	Considerable loss of strength
>450^{0}C	**Cold worked steel**	Loss of residual strength
>600^{0}C	**Hot rolled steel**	Loss of residual strength

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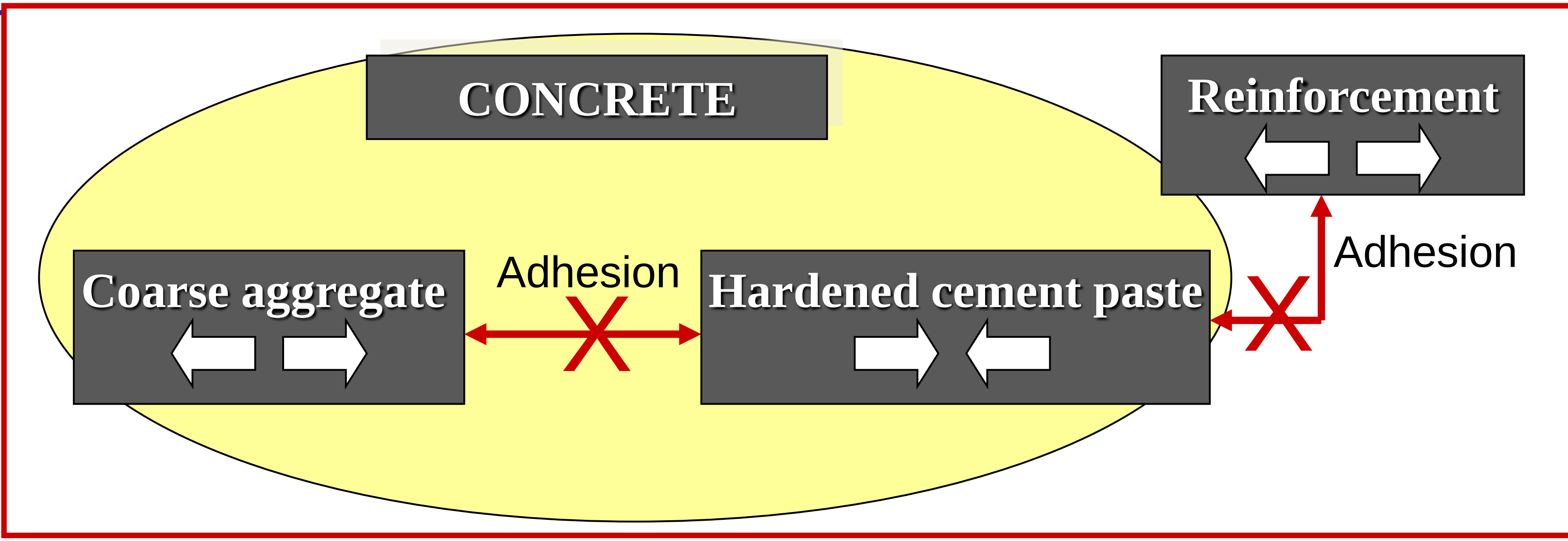

Basic visible damages of reinforced concrete

CONCRETE	REINFORCING BARS
Spalling	Plastics deformation
Cracking	Breaking of

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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.

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Theories explaining spalling

- **Main theories**
  - Thermal stress theory
  - Pore pressure theory
  - Combined pore pressure and thermal stress theory
- **Specific theories**
  - Fully saturated pore pressure theory
  - BLEVE - Boiling liquid expanding vapour explosion theory
  - Frictional forces from vapour flow theory

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

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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.)

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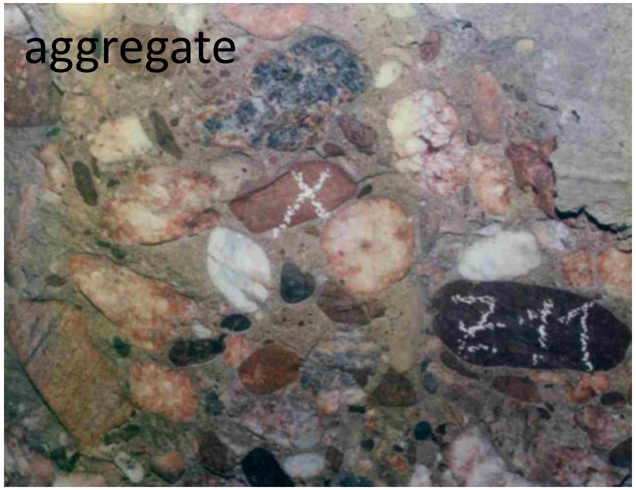
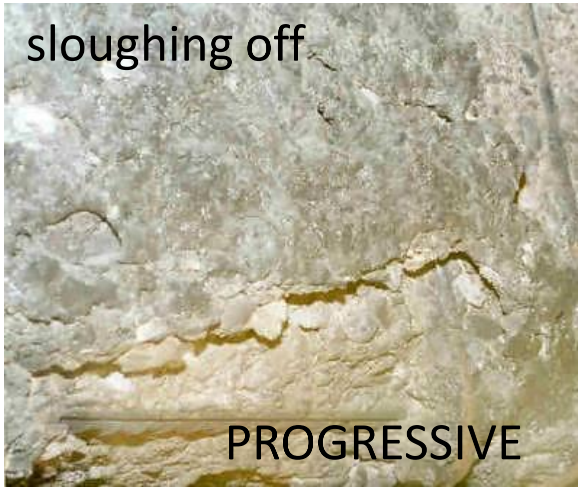
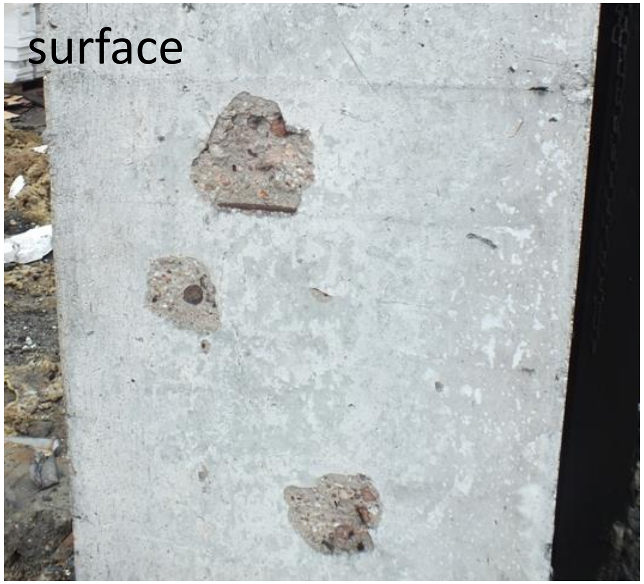
TYPES OF THERMAL SPALLING







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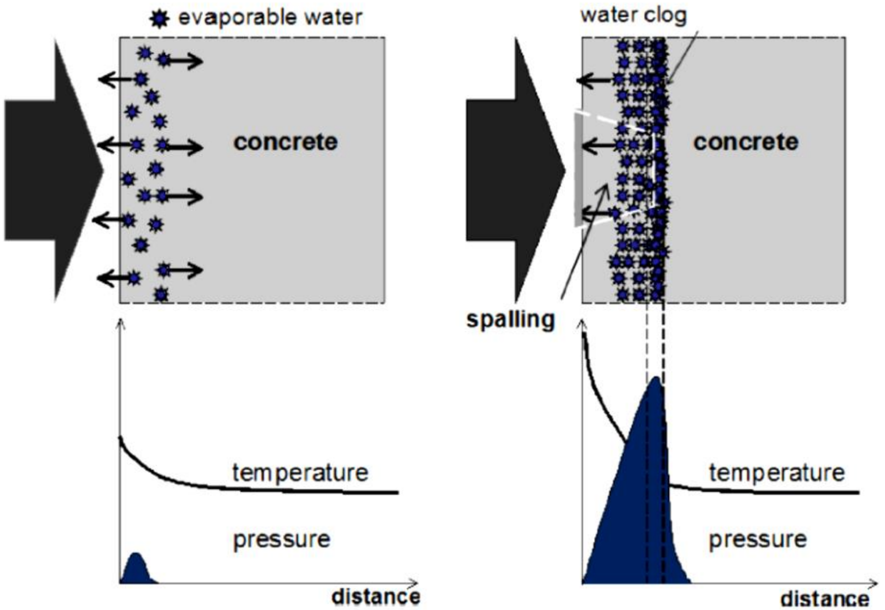
EXPLOSIVE SPALLING

Explosive spalling occurs:

- rapid temperature rise > 30^{0}C/min
- concrete reaches 150-250^{0}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

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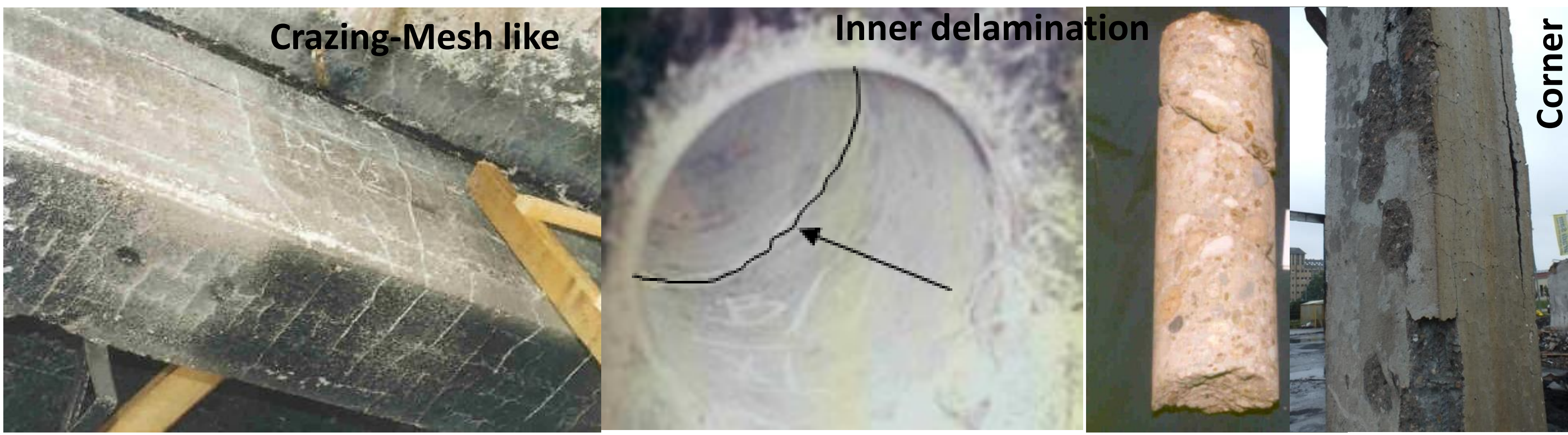
CRACKING

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



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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.

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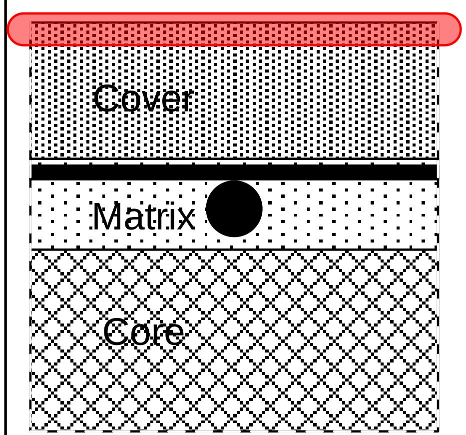
CLASSIFICATION OF DAMAGES

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
1	Surface thin layer	 	Minor crazing – mesh like fissures with normal concrete colour Spalling is non-visible Rebars are non-visible

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Damage degree	Affected part of cr./sect.	Illustration	Features observed
2	Concrete cover	  	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%)

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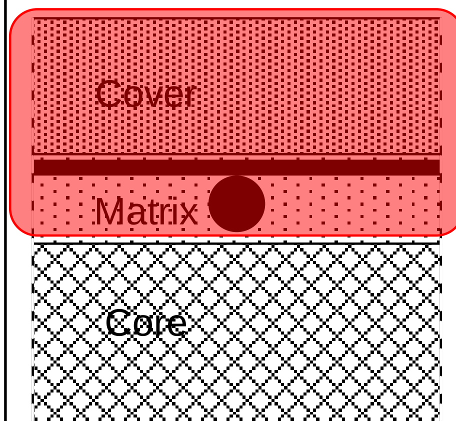
Damage degree	Affected part of cr./sect.	Illustration	Features observed
3	Concrete matrix	 	Extensive crazing Corner spalling and cracks along rebars Sloughing off sp. Change of concrete colour (pink/red/whitish grey) < 50% of rebars are visible Loss of concrete strength Minor deflection of RC elements

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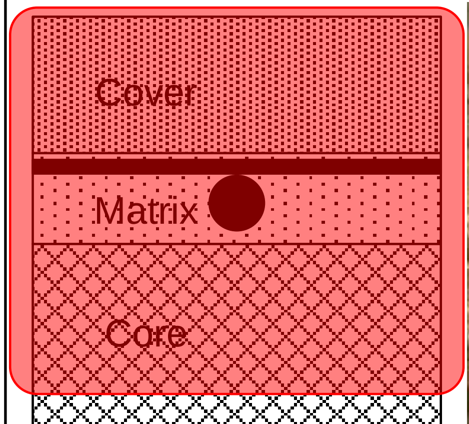
Damage degree	Affected part of cr./sect.	Illustration	Features observed
4	Concrete core	  	Deep extensive spalling > 50% of rebars are visible Change of concrete colour: whitish grey/buff Possible melting of concrete Inner delamination of concrete Impaired bond between concrete and rebars Possible buckling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

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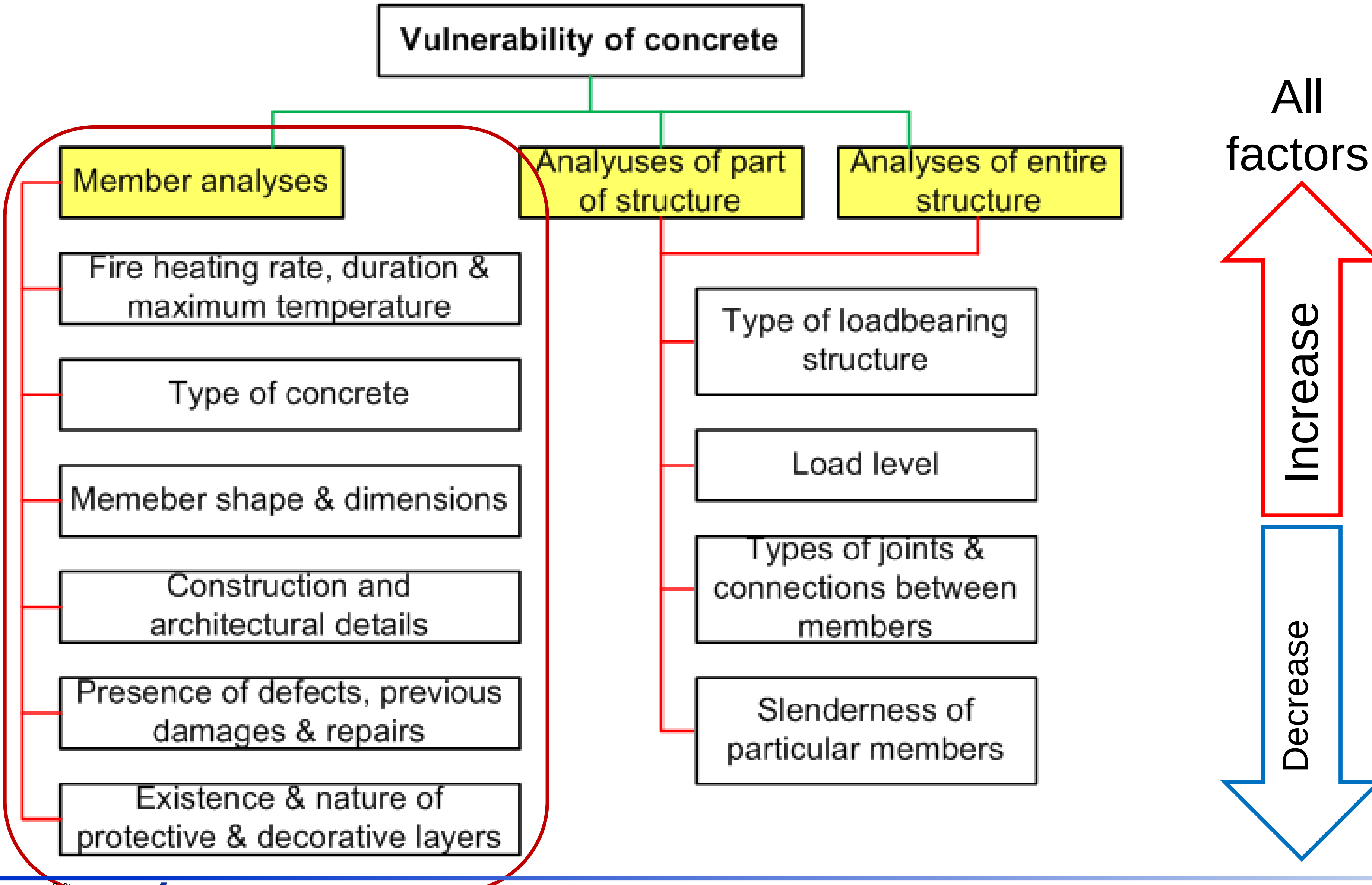
VULNERABILITY OF CONCRETE STRUCTURES DUE TO FIRE



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MEMBER ANALYSIS – Type of concrete

:ORDINARY/NORMAL WEIGHT CONCRETE (OC/NWC)

Vulnerability of OC

- **Origin of aggregate**
  - **Silliceous**
    - Better thermal stability up to 600^{0}C: Basalt, Granite, Gabro
    - Lower thermal stability below 350^{0}C: Flint, River aggregate, Metamorfic rocks
  - **Calcerous**
    - Better thermal stability up to 650^{0}C: than silliceous aggregate
- **Moisture content**
  - **<3%**: Less prone to explosive spalling

Khory class.

Better bond

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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

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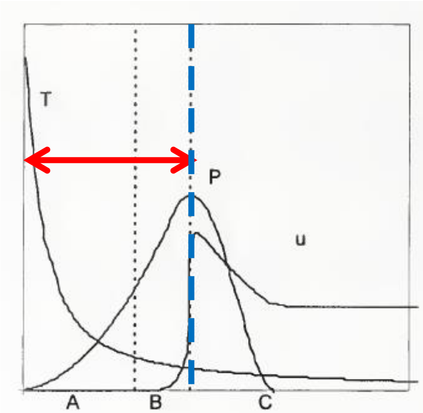
MEMBER ANALYSIS – Type of concrete
:HIGH STRENGTH CONCRETE (HSC)

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

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

OC

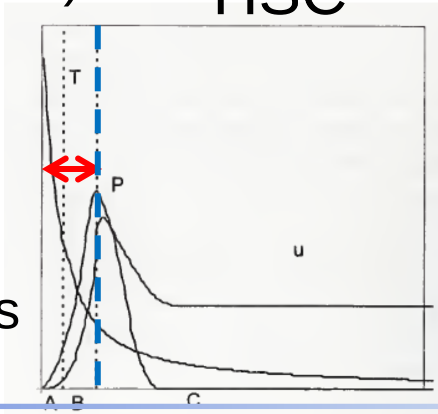


HSC <=> NWC

DISADVANTAGES

- Higher – great risk to expolossive spalling
  - Earlier occurence
  - More prone to spall at concrete moisture ≥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^{0}C up to 30%)
  - Redistribution of internal sresses (due to weakness of cement matrix)

HSC



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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.

Type of fibres

- **Incombustible**
  - Steel fibres
    Glass fibres
    Basalt fibres
- **Combustible**
  - Syntetics fibres: PP,PE, NY, ACRYL...
  - Natural fibres: Coconut, bagasse...

Most used fibres

SF - Steel fibres

Effectiveness in mitigating explosive spalling

?

PPF - Polypropylene fibres

Effectiveness in mitigating explosive spalling

YES

Due to micro-channels generating by melting of PPF

Effect of PPF on explosive spalling

OC PP FRC

Recommendation:

EC2: min 3kg/m^3

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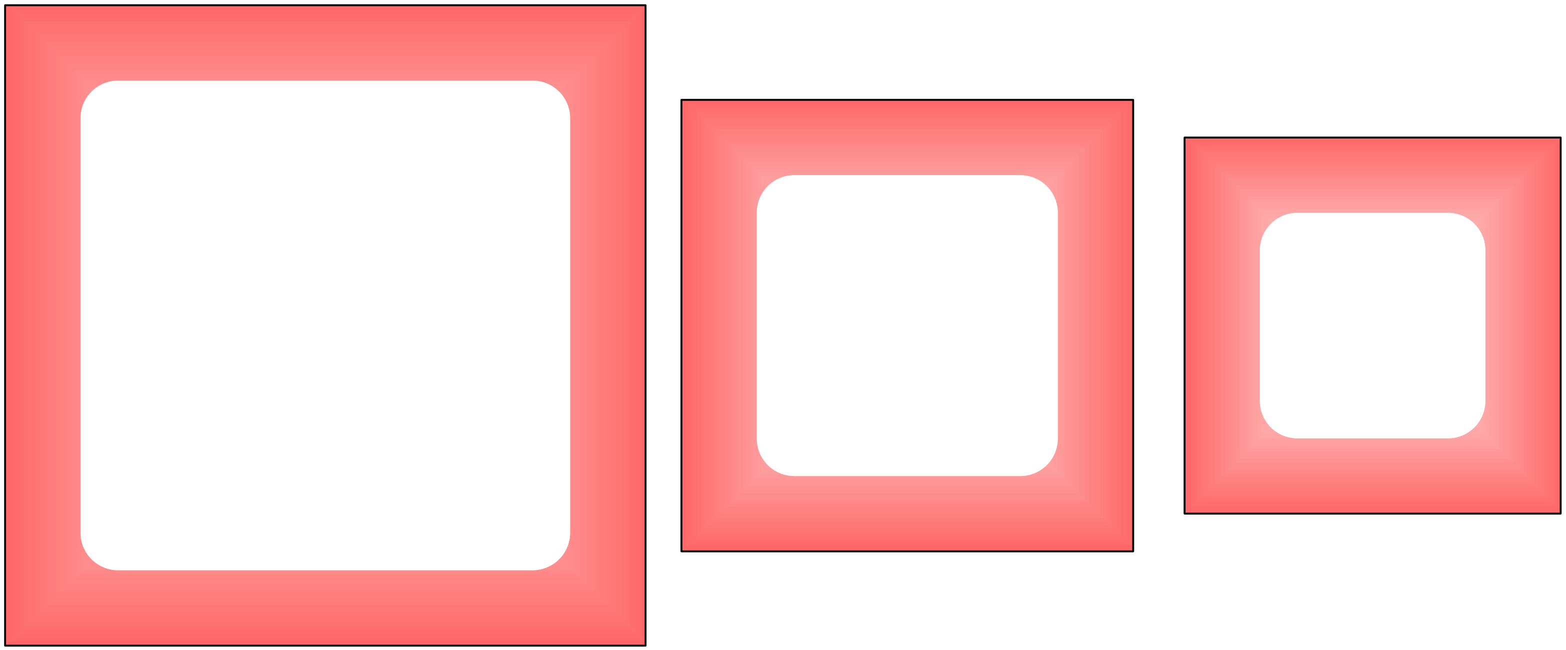
MEMBER ANALYSIS – Construction details

- Shape & dimensions of cross section:



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

Progressive heat penetration

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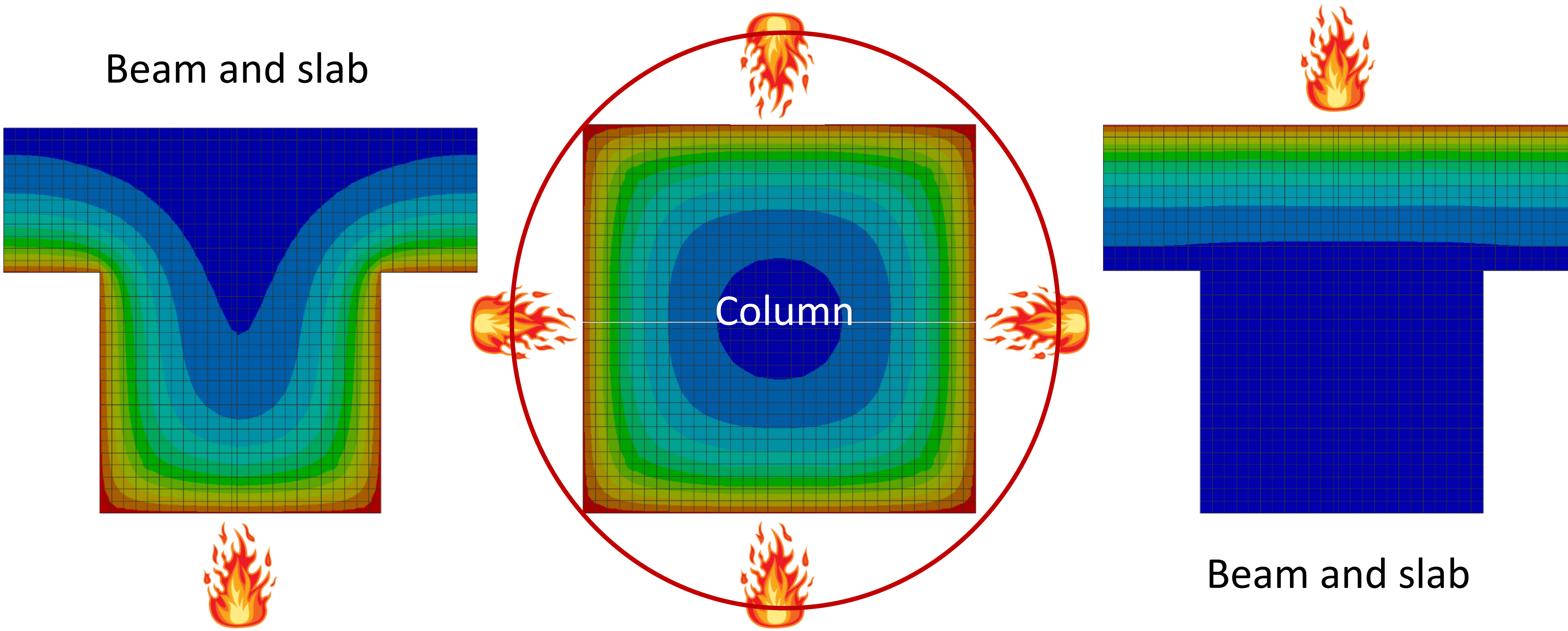
MEMBER ANALYSIS – Construction details

- Position of member:



Progressive heat penetration
Most intesive spalling

MEMBER ANALYSIS – Construction details

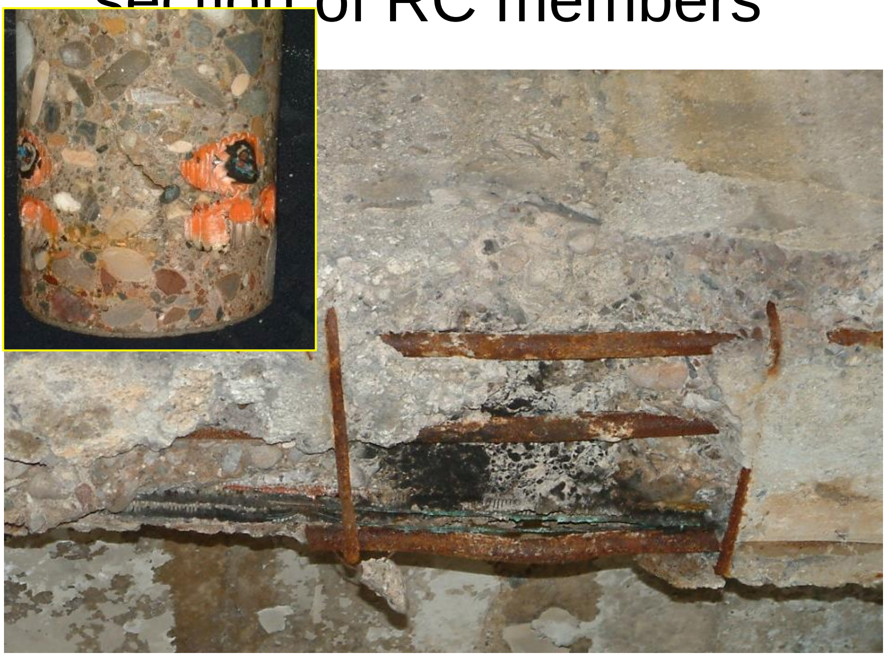
- Shape & dimensions of cross section:
- Arragement of reinforcement

Progressive heat penetration
Most intesive spalling

Rebars with larger diameter and inadequate layout contribute to the intensification of damages

MEMBER ANALYSIS –
Construction and architectural details

- Placement of electrical & similar installations within cross-section of RC members



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

MEMBER ANALYSIS – Constr. & arch. details

- Holes for penetration of installations

Inadequate sealing of holes=Faster & direct fire spreading

- Presence of defects, previous damages & repairs

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

Local deep overheating of concr. Serious spalling

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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,

combustible

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.

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