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FIRE DAMAGES OF REINFORCED CONCRETE STRUCTURES AND REPAIR POSSIBILITIES

Abstract: This paper discusses causes and appearance of characteristic damages, vulnerability and repair methods of RC structures exposed to fire. Complexity of behaviour of reinforced concrete at elevated temperature is pointed out through theoretical description and consideration of different damage mechanisms. Characteristic fire damages of concrete and steel are described, illustrated and classified with respect to affected part of cross-section of the RC structural elements. Depending on the extent of damage, several methods for concrete removal are suggested. Basic repair principles are classified regarding affected part of the cross-section and state of the reinforcement.

Key words: fire, concrete, RC structures, vulnerability, damages, repair methods

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1. INTRODUCTION

Properly designed and successful execution of repair work of RC structure damaged in fire can only be provided if a detailed in-situ and laboratory investigation and correct assessment of residual structural capacity have been made. Recommendations available from various sources (books, codes, articles etc.) could help to choose appropriate solution from a wide range of available repair methods and repair materials, but in practice every single fire damaged structure is unique [20]. For realistic assessment of the structure after a fire it is necessary to know 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. Reinforced concrete is considered a material that shows an acceptable resistance to high temperatures, which allows using concrete elements without the need of any additional protection. The main reason for this statement are the following properties of the concrete: incombustibility, small thermal conductivity, small strains at rising temperatures and therefore concrete core remains intact inside the section of element and continues transmit load. On the other hand, reinforcement is sensitive to high temperatures and needs to be protected. In RC structures concrete cover plays that role. The relatively low thermal conductivity of concrete leads to a slow propagation of chemical transformations of the components of concrete, which also need time for fully developing conversions at each specific temperature. On the other hand, low thermal conductivity of concrete causes strong thermal gradient that induce internal stresses in concrete mass and development of inner cracks [1]. However, long period of exposition of reinforced concrete to high temperatures introduce physical-chemical changes in its properties that lead to mechanical strength decay which produces losses in the bearing capacity and safety of the structure.

2. DAMAGE MECHANISMS OF CONCRETE UNDER FIRE

Concrete is a composite material that consists mainly of mineral aggregates bound by a matrix of hydrated cement paste. The matrix is highly porous and contains a relatively large amount of free water. When subjected to heat, concrete responds not just in instantaneous physical changes, such as expansion, but by undergoing various chemical changes. This response is especially complex due to the non-uniformity of the material. Concrete contains both cement and aggregate elements, and these may react to heating in a variety of ways [7]. The main changes occur primarily in the hardened cement paste. With the increase of temperature in concrete to 100^0C free water from the capillary pore system of hardened cement paste will be evaporated. In the range of 100^0C - 400^0C the cement paste loses physically bond water, while at temperatures above 400^0C chemically bound water will be lost. The following chemical transformations can be observed by increase of temperature: the decomposition of ettringite between 50^0C and 110^0C, endothermic dehydration of $Ca(OH)_2$ at the temperatures 450^0C-550^0C and dehydration of calcium-silicate-hydrates at the temperature of 700^0C [2]. The loss of pore water and chemical transformations are accompanied by shrinkage of cement stone. On the other

hand, due to rising temperatures, coarse aggregate increases its volume and disruption of adhesion between the cement paste and coarse aggregate appeared. In the case of reinforced concrete, the same mechanism leads to impaired adhesion between the reinforcement and concrete [20].

Aggregate normally occupy 65 to 75% of the concrete volume, and that is why the behavior of concrete at elevated temperature is strongly influenced by the aggregate type. Commonly used aggregate materials are thermally stable up to 300^0C–350^0C. Aggregate used in concrete can be classified into three types: carbonate, siliceous and lightweight aggregate (LWA). Carbonate aggregates include limestone and dolomite. Siliceous aggregate include materials consisting of silica and include granite and sandstone. LWA are usually manufactured by heating shale, slate, or clay. Compressive strength of concrete containing siliceous aggregate begins to drop off at about 400^0C and is reduced to about 55% at 650^0C because of change of crystal structure of quartz α formation → β formation [2]. Concrete containing LWA and carbonate aggregates retain most of their compressive strength up to about 650^0C. Lightweight concrete has better insulating properties, and transmits heat at a slower rate than normal weight concrete with the same thickness, and therefore generally provides increased fire resistance. The modulus of elasticity for concretes manufactured of all three types of aggregates is reduced with the increase in temperature. Also, at high temperatures, creep and relaxation of concrete increase significantly. The colour of concrete generally changes at increasing temperature from normal to pink or red (300-600^0C), whitish grey (600-900^0C) and buff (900-1000^0C). If the concrete temperature exceeds 1300^0C, the softening and melting of surface layer will be occur [20]. Described physical and chemical changes in concrete will have the effect on reduction of the compressive strength of the material. Generally, concrete will maintain its compressive strength until a critical temperature is reached, above which point it will rapidly drop off. This generally occurs at around 600^0C [7].

Reinforcing steel is much more sensitive to high temperatures than concrete. Both materials are incombustible but concrete has protective i.e. insulating role. Hot-rolled steels (reinforcing bars) retain much of their yield strength up to about 400^0C, but at temperatures >600ºC hot-rolled steel loses residual strength. Cold-drawn steels (prestressing strands) shows considerable loss of strength at 200-400ºC. Cold-worked steel loses residual strength at temperature >450ºC. Reducing the strength of reinforcement at high temperatures is usually the cause of the large permanent deflection of the structure.

When concrete is exposed to high temperature, as in the case of fire, the basic visible damages are thermal spalling and cracking, but other changes take place also, like a drop of strength and modulus of elasticity and change of colour. In most cases, a combination of these fire effects is registered.

Spalling is an umbrella term, covering different damage phenomena that may occur to a concrete structure during fire [4]. Spalling could be defined as 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 as experienced in fires [13]. These phenomena are caused by different mechanisms [4]:

- 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 tu chemical transitions during heating.

There are several main theories explaining the spalling mechanisms [11, 12]:

- Thermal stress theory
- Pore pressure theory
- Combined pore pressure and thermal stress spalling.

During last few decades several specific theories were developed [11]:

- The fully saturated pore pressure theory
- The BLEVE theory (Boiling Liquid Expanding Vapour Explosion)
- The 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.

Cracking of concrete exposed to fire occurs due to exceeding of concrete tensile strength. Cracks and fissures are caused by thermal expansion and dehydration of the concrete due to heating.

3. TYPES AND CLASSIFICATION OF DAMAGES

3.1. Types of damages

Term "**spalling**" encompasses large number of damage types. The first types of spalling were described in the beginning of the 20th century (explosive, surface, aggregate and corner spalling). Over the next decades two new types were added (sloughing off spalling and post cooling spalling) [4, 13]. They are:

- **Explosive spalling:** Violent breaking off of concrete fragments at high temperatures generally occurs in the first 30 minutes of a fire. Explosive spalling is usually caused by: insufficient release of high pore pressure, high thermal stresses and combination of both. This type of spalling is especially likely to occur on structural members heated from more than one side, such as columns and beams. When moisture clogs are advancing into the concrete from all heated sides, at some point in time the moisture clogs will meet in the centre of the cross-section, giving a sudden rise in pore pressure which may cause large parts of the cross-section to explode.
- **Surface spalling**: Violent separation of small or larger pieces of concrete from the cross section at high temperatures, during which energy is released in the form of

popping off of the pieces and small slices with a certain speed. Usually occurs in the first 30 minutes of a fire.

- **Aggregate spalling**: Splitting of aggregates due to their decomposition or changes at high temperatures. Usually occurs in the first 30 minutes of a fire (Fig. 1).
- Corner spalling: Removal of concrete cover from corners at high temperature due to the temperature impact from two sides. This type of spalling is usually connected with splitting cracks due to difference in thermal deformation between concrete and reinforcement and occurs in the first 90 minutes (Fig. 2).
- **Sloughing off spalling**: Sloughing off is the form of progressive gradual spalling, that is caused by strength loss due to internal cracking and chemical deterioration of the cement paste.This type of spalling is non-violent breaking off of concrete fragments after longer exposure to high temperatures, when concrete loses its strength (Fig. 3 and 4).
- **Post-cooling spalling:** Non-violent breaking off of concrete fragments during cooling from high temperature. This type of spalling was observed with concrete types containing calcareous aggregate. An explanation is the rehydration of CaO to $Ca(OH)_2$ after cooling, when moisture is again present on the concrete surface. The expansion due to rehydration causes severe internal cracking and thus complete strength loss of the concrete. Pieces of concrete keep falling down as long as there is water to rehydrate the CaO in the dehydrated zone (Fig. 5).

The term “cracking” covers the following types of damage:

- **Crazing**: Mesh like fissures and cracks on the surface of the concrete elements (Fig. 6), caused by additional shrinkage of hardened cement paste during drying due to high temperature.
- **Corner cracks along main reinforcement**: Cracking due to difference in thermal expansion/deformation between concrete and reinforcement bars. These cracks are usually located along the edge of columns and beams, especially in the direction of the main reinforcement. Also, they are associated with the separation and falling off of pieces of concrete (corner spalling) and with visible reinforcement bars (Fig. 2).
- **Inner delamination of concrete**: Is manifested as internal crack parallel to the fire-affected surface (Fig. 7). The main cause of this damage is high temperature gradient that induces high tensile stresses between the heated surface layer and colder inner zone of concrete. This phenomenon is typical for the columns. Since the internal cracks cannot register visually, their existence must be checked by extracting concrete cores

Concrete surface cracking may provide pathways for direct and faster heating of the reinforcement bars and inner concrete, possibly bringing about more thermal stress and further cracking.

Loss of strength and ductility of reinforcement are usually consequences of high temperatures during fire. Visible characteristic fire damages of reinforcement are:

- Plastic deformations due to restrained elongation (Fig. 8).
- Breaking of bars (Fig. 8) due to loss of ductility of the steel or local reduction of bar cross section because of melting of steel.

Reinforced concrete elements during fire are subjected to additional stresses due to restrained deformations. In a case of slender beams and slabs buckling associated with deflection may occur. Under fire conditions, axially restrained beam/slab develops large deflections in post-buckling states [23].

Extent and type of described fire damages of RC structures depends on numerous parameters, among which the most important are: size and distribution of fire load, fire duration, fire maximum temperature, the shape and dimensions of structural elements, the existence and type of finishing layer - cover of the RC elements, the presence of defects and/or prior damage, construction details and the actual quality of concrete.

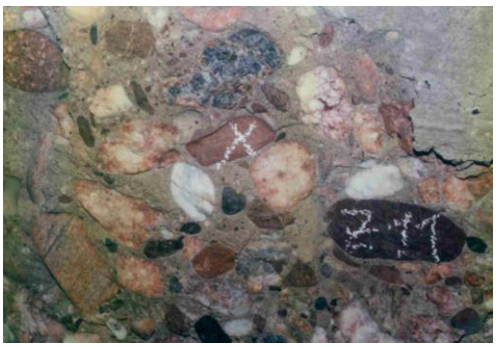


Figure 1: Aggregate spalling

Figure 2: Corner spalling and corner cracks along main reinforcement

Figure 3: Sloughing off spalling (beam)

Figure 4: Sloughing off spalling (slab)

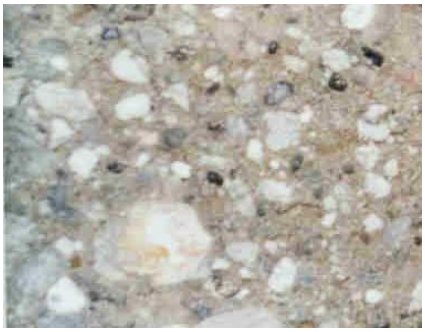


Figure 5: Post-cooling spalling

Figure 6: Crazing – mesh like cracks

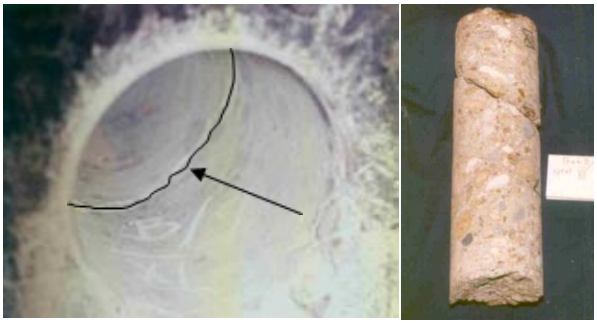


Figure 7: Inner delamination of concrete in the column

Figure 8: Plastic deformations and breaking off of bars

3.2. Classification of damages

Among a numerous available classification of concrete fire damages authors of this paper chose the classification proposed by Ingham and Tarada [10] and modified it in relation to the degree of affected part of RC element cross section. Figure 9 illustrates parts of cross section of typical RC element that have to be considered during selection of appropriate repair method. Proposed classification is given in Table 1.

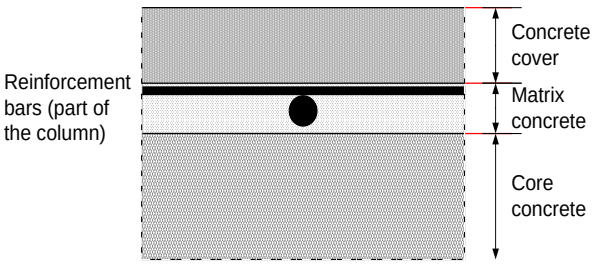
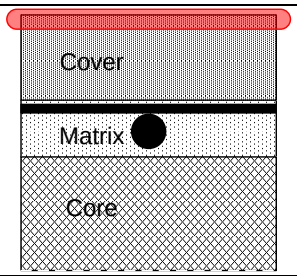
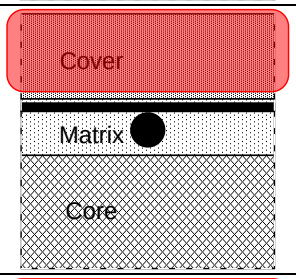
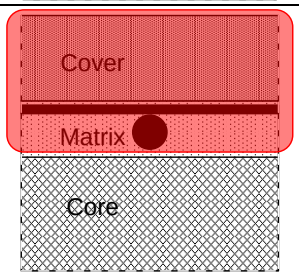
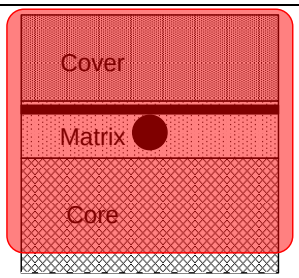


Figure 9: Characteristic parts of cross section of RC element

Table 1: Classification of fire damages with illustration of affected part of cross-section

Damage degree	Affected part of cross-section	Illustration	Features observed
1	Surface thin layer		Minor crazing – mesh like fissures with normal concrete colour Spalling is non-visible Rebars are non-visible
2	Concrete cover		Moderate crazing - mesh like cracks Surface spalling Aggregate spalling Change of concrete colour (pink or red) Rebars are non-visible or locally visible at places with insufficient cover (up to 25%)
3	Concrete matrix		Extensive crazing Corner spalling and cracks along rebars Sloughing off spalling Change of concrete colour (pink/red/whitish grey) Up to 50% of rebars are visible Loss of concrete strength Minor deflection of RC elements
4	Concrete core		Deep extensive spalling More than 50% of rebars are visible Change of concrete colour (whitish grey/buff) Possible melting of concrete (long-lasting fires) Inner delamination of concrete Impaired bond between concrete and rebars Increase of deflection of RC elements Reduction of rebars mechanical properties Possible buckling and breaking off of rebars

4. VULNERABILITY OF CONCRETE STRUCTURES EXPOSED TO FIRE

According to EN 1992-1-2 [5] fire resistance design of the construction requires three levels of analysis:

- Member analysis,
- Analysis of part of the structure and

- Analysis of entire structure.

Besides heating rate, duration and maximum temperature of the fire, vulnerability of RC structures exposed to fire on member level depends on numerous additional factors, such as:

- Type of concrete (ordinary concrete, lightweight concrete, high strength concrete, fiber reinforced concrete, self-compacting concrete, etc.)
- Shape and dimensions of the structural members (simple/compact or complex cross sections)
- Construction and architectural details (concrete cover thickness, reinforcement arrangement, placement of installations)
- Presence of defects and previous damages and repairs (honeycombs, insufficient concrete cover, poor cold joints, cracks)
- Existence and nature of protective and decorative layers (combustible and incombustible layer materials).

4.1. Member analysis

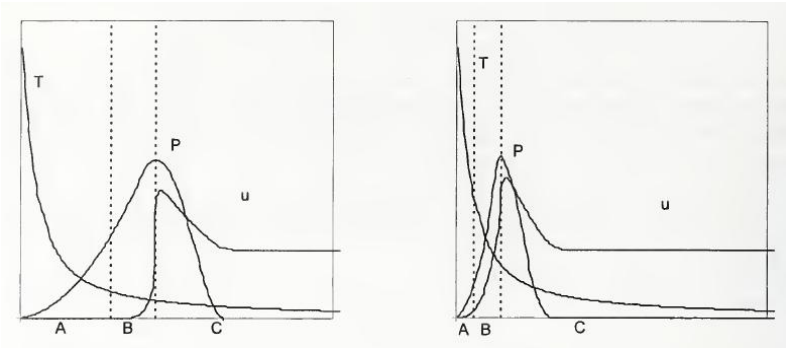
4.1.1. Concrete type

Fire properties of *ordinary concrete (OC, NWC)*, as well as other types of concrete, mainly depends on aggregate type, as aggregates occupy 65-75% of the volume of concrete. In EN 1992-1-2 [5] aggregate is split in two groups, siliceous and calcareous aggregate. Calcareous aggregate has better fire properties than siliceous aggregate. However, some authors propose different siliceous aggregate classification. For example Khoury [14] divided siliceous aggregate in two groups, with better thermal stability (up to 600^0C) such as basalt, granite and gabbro and with lower thermal stability (below 350^0C) like flint and river aggregate. From the aspect of thermal stability, the least favourable aggregates are those obtained from rocks of metamorphic origin, primarily of quartzite rocks. Namely, quartzite rock contains a significant amount of mineral quartz, which is considered as the most critical mineral of solid rock at elevated temperatures [3]. Considering concrete behaviour at high temperature, besides thermal stability, a suitable aggregate would be one with a low thermal expansion, which improves thermal compatibility with the cement paste, rough angular surface, which improves the physical bond with the cement paste and the presence of reactive silica, which improves the chemical bond with the cement paste [14].

Lightweight aggregate concrete (LWAC, LWC). Concrete with artificial mineral lightweight aggregate, such as expanded clay, is the most frequently used type of LWAC for structural purpose. Structural lightweight concrete is advantageous in terms of reducing the dead load of the structures and the lateral earthquake loads. In addition to lower density, this type of concrete has a lower thermal conductivity and transmits heat at a slower rate than ordinary concrete. However, LWAC tends to have a reduced tensile strength compared to NWC, for the same compressive strength. The replacement of traditional aggregates by lightweight aggregate generally results in an increase in the

occurrence of spalling for temperatures above 350 °C. The occurrence of spalling in LWAC is due to its lower tensile strength, higher moisture content and the development of higher thermal gradient during heat exposure. When spalling does not occur, the deterioration of LWAC due to elevated temperatures is similar to OC [25] or smaller, thanks to lightweight aggregate that has already been exposed to temperature >1000^{0}C during Pyroprocessing. In fact, the residual strength is generally higher in LWAC than in OC due to the higher thermal compatibility of the constituents of LWAC. Since, the difference between the coefficients of thermal expansion of the aggregate and the cement paste is higher in the OC than in LWAC, the OC is more prone to cracking. Also, LWC protects more efficiently the tension bars from the heat flow, with a remarkable increase of the bearing capacity at any fire duration [19].

High strength concrete (HSC). Thanks to technical and economic benefits HSC is increasingly becoming a key component in large-scale construction, from tall commercial and residential buildings to bridges, tunnels and offshore structures. The basic properties of HSC are high compressive strength and modulus of elasticity (stiffness), decreased permeability and abrasion resistance. Fire-exposed HPC has a different tendency and feature of spalling compared with OC. Due to the low permeability of HPC, which makes it more difficult to transport vapour and moisture, very high vapour-pressure may occur close to the surface [18]. This means that there is a greater risk that HPC spalls compared with OC. When the vapour zone moves to a certain distance from the hot surface, a maximum vapour pressure is created, and at greater distances the pressure decreases again. This critical distance is much less for HPC, about 5-10 mm than for OC, about 20-40 mm (Fig. 12). It has been observed from fire tests that spalling of HPC is characterized by a layer of about 5 mm of concrete falling off and after that a new vapour front buildup, which can create a new spalling of 5 mm, and in the end the total spalling can reach considerable depths [18]. The Compressive strength decrease of HSC begins at distinctly lower temperatures than that of OC. For example, at 150^{0}C compressive strength of HSC decreased to 70% of its room temperature strength, while reduction of compressive strength in OC is negligible. In HPC cement matrix and coarse aggregate are loaded with same stress level, because they have similar values of modulus of elasticity and compressive strength. At elevated temperatures cement matrix begins to weak before coarse aggregate and it causes redistribution of internal stresses and the stress is concentrated on the coarse aggregate alone which lead to significant reduction of the compressive strength of HPC. On the other hand, weakening of the cement matrix due to heating causes only slight stress redistribution and consequently only a little bit reduction of compressive strength of OC [8]. HSC exhibits brittle properties below 600^{0}C, and ductility above 600^{0}C.



A – dry concrete
B – vapour zone
C – moist concrete
T – temperature
P – vapour pressure
U – moisture content
OPC – left
HSC - right

Fig. 12. Illustration of water clog position and internal pore pressure within heated OC and HCC

Fiber reinforced concrete (FRC). Fiber reinforced concrete (FRC) is concrete containing fibrous material which increases its structural integrity. It contains short discrete fibers that are uniformly distributed and randomly oriented. Fibers include steel fibers, glass fibers, synthetic fibers and natural fibers. Steel, glass and other mineral fibers are incombustible, while organic synthetic and natural fibers are combustible. Among the mentioned fibers steel and polypropylene fibers are commonly used in concrete. So far a number of tests have been done to investigate the explosive spalling of concrete with PP fibers or steel fibers or steel/PP hybrid fibers. In FPC PP fibers are deemed to be effective in mitigating spalling risk under fire due to micro-channels generated by melting of PP fibers (Fig. 13) [26]. PP fibres melt at approximately 170^0C, and leave a network of open pores, which make steam evacuation easier, thus contributing to the reduction of internal pore pressure [24]. Eurocode had prescibred that 3kg/m^3 PP fibers can help avoid spalling. The diameter, length and amount of PP fibers have significant effect on reduction of spalling of concrete in fire, as well as on concrete compressive residual strength (Fig. 14) [27] For SFRC different conclusions were made about the effectiveness in mitigating explosive spalling under fire.

Fig. 13. A view of OC (left - explosive spalling) and PPFRC (right) after exposing to elevated temperatures

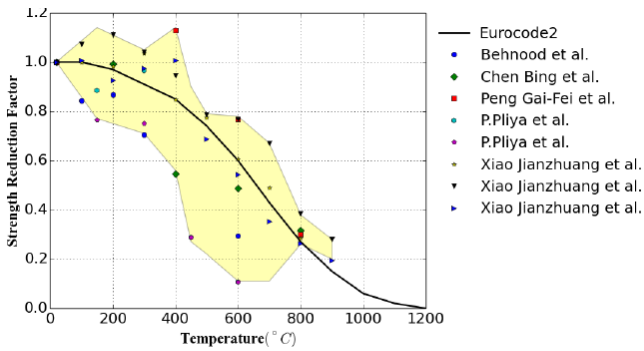


Fig. 14. Compressive strength reduction against temperature for PP-FRC with (a) calcareous aggregates

4.1.2. Construction and architectural details

The arrangement of reinforcement in the structural members also has an impact on the degree of fire damage. Rebars with larger diameter and inadequate layout of reinforcement contribute to the intensification of damages caused by fire, especially in members with smaller dimensions or with insufficient cover (Fig. 16). Characteristic damages are falling off of concrete cover and plastic deformations of bared reinforcement.

Placement of electrical and similar installations within cross-section of RC elements frequently leads to significant local damage of concrete and reinforcement. The installations in buildings are usually placed in plastic pipes which melt and burnt during fire and realise additional heat and causes local damage of concrete core following with plastic deformation of rebars. Fig. 17 illustrates local severe damages of beam and slab, respectively, due to afterburning of installations in plastic pipes.

Inadequate sealing of holes for penetration of installations enables uncontrolled and fast fire spreading. Fig. 18 illustrates fast spreading of fire in both vertical directions caused by unsealed holes for installations in floor slabs and curtain façade wall without horizontal barriers.

4.1.3. Presence of defects and previous damages and repairs

Defects (concrete honeycombing, segregation zones, improperly executed cold joints, insufficient concrete cover, uneven edges, etc.) and damages (cracks) that existed before fire significantly increase the damage rate of RC members exposed to fire. In such zones, fire damages are spreading faster and deeper into the concrete mass and usually occupy concrete matrix and even concrete core. Characteristic damages are falling off of thick pieces of concrete, impaired bond between the reinforcement and concrete, plastic deformation of the rebars, as well as local reduction of concrete mechanical properties. Influence of improper executed cold joint in the pan joist on the degree of fire damages is shown in Fig. 19.

4.1.4. Existence and nature of protective and decorative layers

Inorganic mineral coatings of concrete surfaces (mortar, plasterboard, ceramic and stone tiles) play a very important role in protecting RC members during the fire. The advantages of these materials in fire are two-fold. They are incombustible and also good insulating materials possessing a low thermal conductivity. However, inorganic mineral materials are not refractory materials they will gain serious damages and even could be destroyed during the fire. Although these coatings are relatively thin (2-5 cm thick) they will prevent RC members from rapid heating and appearance of serious damages and increase their fire resistance. On the other side, organic coatings (wood, plastics, textiles, etc.) are combustible materials and contribute to local development of high temperature on the surface of RC members which leads to intensification of their fire damages. Influence of coating type on the fire damage degree of concrete columns is shown in Fig. 20.

Fig. 15. Typical damages of pan joist floor system due to fire

Fig. 16. Characteristic damages of improper reinforced rib due to fire

Fig. 17. Local deep overheating of concrete and deformed rebars due to wirings within cross-section (a – beam, b – slab)

Fig. 18. Spreading of fire in both vertical directions [9]

Fig. 19. Influence of defects on fire damages degree in pan joist floor system

Fig. 20. Influence of type of decorative layer type on the fire damage degree of concrete columns

5. METHODS FOR CONCRETE REMOVAL

Before beginning the repair and strengthening of the structure it is necessary to remove all additional loads and to support the structure. Besides preserving the stability of the structure during repair works, these activities are important in cases of structural repair where the new concrete is expected to carry its share of the load in the repaired elements. In the scope of repair very important role play proper selection of a method for concrete removal. Since there are a number of methods for concrete removal which differ in possibilities and limitations of application, it is not easy to select appropriate method. Depending on the damaged part of cross-section, authors of this paper propose following methods for concrete removal (Fig. 28).

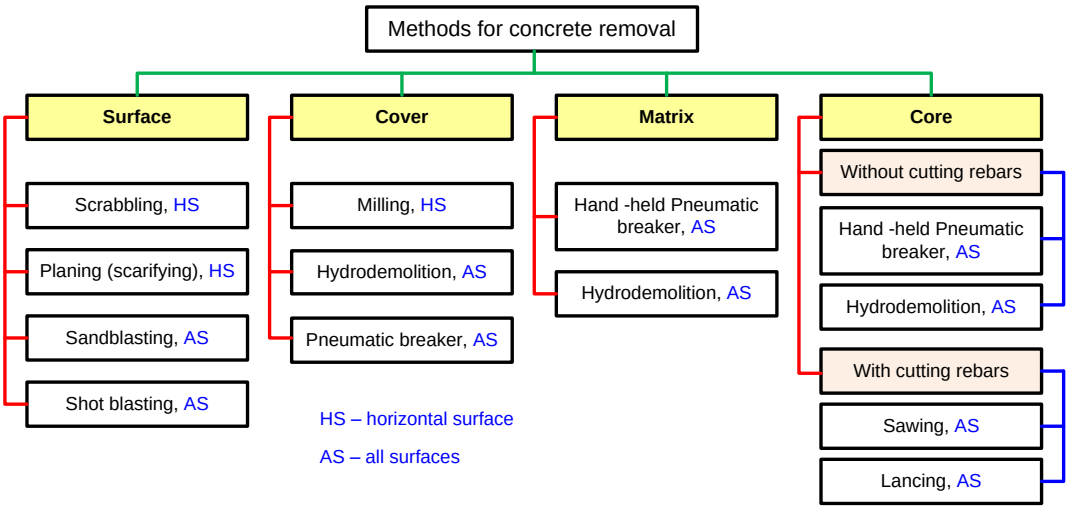


Fig. 28: Suggested methods for concrete removal

6. SELECTION OF REPAIR METHOD AND MATERIAL

Based on the recommendations for repair of fire damaged RC structures in analysed literature [6], [21], [22] and on authors professional experience [15], [16], [17] decision about general repair strategy (structural or non-structural repair) mainly depends on affected part of the cross-section and state of the reinforcement. Non-structural repair is proper choice if rebars are not or locally visible. In all other cases structural repair is required, when: reinforcement is visible, bond is destroyed, rebars have plastic deformations, structural elements have excessive deflections etc. Structural repair is also mandatory in situation when all pointed out features are not accented but inner delamination of concrete exists. In some cases main reasons for structural repair is doubt regarding remaining structural capacity and intention to provide additional structural safety during future exploitation. For easier decision about type of repair method, Table 2 could be useful. An example of structural repair solution for damaged RC beam is shown on Fig. 29.

Table 2: Suggested repair methods and materials

Damage degree	Affected part of cross-section	General repair method	Short description
1	Surface thin layer	Minor surface repair	Non-structural repair mortar (by hand)
2	Concrete cover	New concrete cover with/without light mesh	Structural mortar (applied by hand or spraying) Sprayed concrete with mesh
3	Concrete matrix	Structural repair and/or minor strengthening	Reinstatement of concrete cross-section with or without partial replacement of damaged rebars (flowable or sprayed concrete with mesh) Enlargement of cross-section and addition of new rebars (flowable or sprayed concrete)
4	Concrete core	Major strengthening or RC element replacement	Enlargement of cross-section and addition of new rebars (flowable or sprayed concrete) New RC element

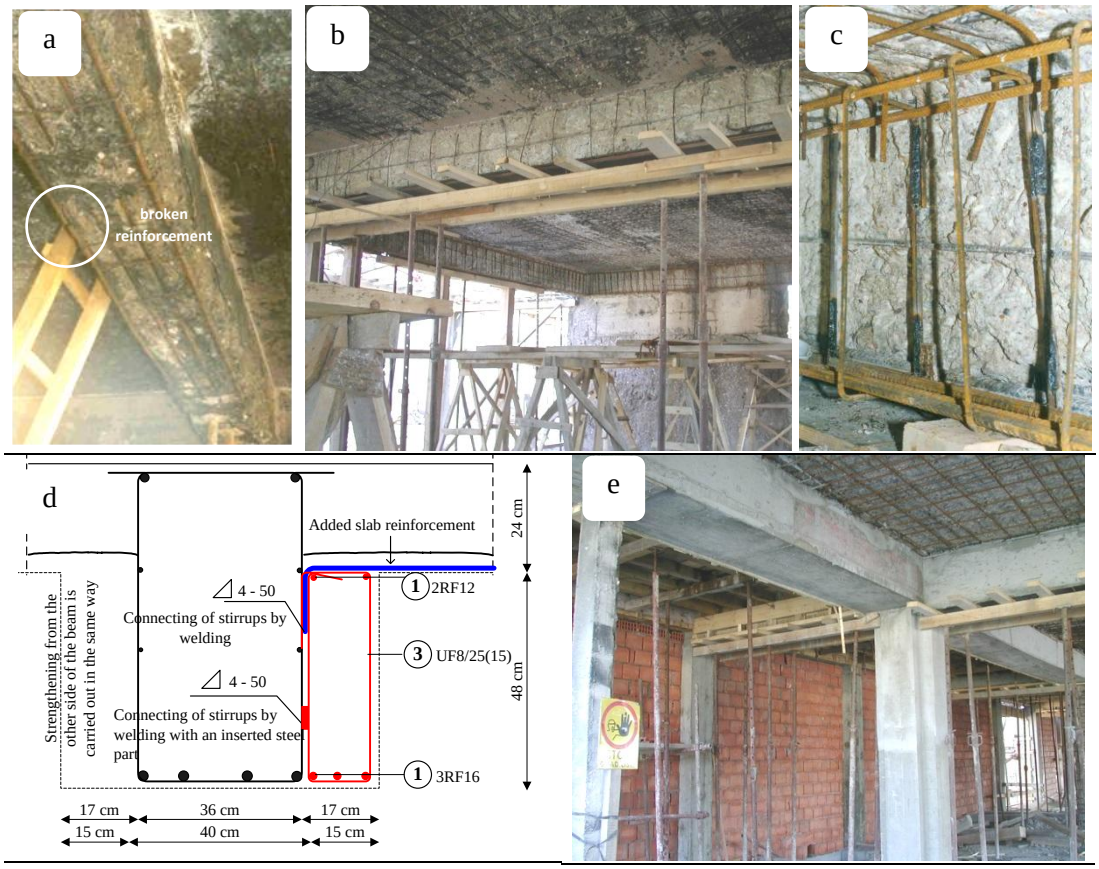


*Fig. 29: Strengthening process: **a)** View of RC beam damaged in fire **b)** Supporting of the beam and removal of damaged concrete **c)** Instalment of new reinforcement **d)** Detail of enlargement of existing cross section and arrangement of reinforcement **e)** Vie of the beam after strengthening*

7. CONCLUSIONS

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 students to understand complex behaviour of reinforced concrete at elevated temperatures and to make decision about possible repair solution.

Through many years of experience in the assessment and repair of the structures due to fire, as well as 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 loadbearing structure, the authors of this paper concluded that 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. 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

8. REFERENCES

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