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POST-FIRE ASSESSMENT AND REPAIR OF REINFORCED CONCRETE STRUCTURES: DAMAGE EVALUATION AND STRUCTURAL REHABILITATION

Summary: Although concrete is classified as a non-combustible material and generally exhibits good fire resistance, exposure to elevated temperatures may significantly reduce the mechanical properties of concrete and reinforcing steel, resulting in cracking, spalling, reinforcement degradation, excessive deformations, and, in severe cases, structural collapse. Following a fire event, reliable assessment of the residual structural capacity is essential for deciding whether damaged structures can be safely repaired and returned to service or should be demolished. This paper presents an overview of the behaviour of reinforced concrete structures subjected to fire, emphasizing the mechanisms of thermal damage, assessment methodologies, and available repair techniques. A case study involving the assessment and rehabilitation of a fire-damaged reinforced concrete building is presented to illustrate the practical application of these methods.

Keywords: RC structures, fire damage, damage assessment, residual load-bearing capacity, structural rehabilitation

PROCENA I SANACIJA ARMIRANOBETONSKIH KONSTRUKCIJA NAKON POŽARA: PROCENA OŠTEĆENJA I KONSTRUKTIVNA SANACIJA

Rezime: Iako se beton klasifikuje kao negoriv materijal i uglavnom pokazuje dobru otpornost na požar, izlaganje povišenim temperaturama može značajno smanjiti mehanička svojstva betona i armirajućeg čelika, što dovodi do pojave pukotina, ljuštenja i otpadanja betona, degradacije armature, prekomernih deformacija i, u težim slučajevima, urušavanja konstrukcije. Nakon požara, pouzdana procena preostale nosivosti konstrukcije od ključnog je značaja za donošenje odluke o tome da li se oštećene konstrukcije mogu bezbedno sanirati i vratiti u upotrebu ili ih je potrebno srušiti. U radu je dat pregled ponašanja armiranobetonskih konstrukcija izloženih požaru, sa posebnim osvrtom na mehanizme nastanka termičkih oštećenja, metode procene i dostupne tehnike sanacije. Prikazana je studija slučaja koja obuhvata procenu stanja i rehabilitaciju požarom oštećene armiranobetonske zgrade, čime je ilustrovana praktična primena navedenih metoda.

Ključne reči: AB konstrukcije, požarno oštećenje, procena oštećenja, preostala nosivost, sanacija konstrukcija

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1. INTRODUCTION

Fire is one of the most severe accidental actions that can affect civil engineering structures. Unlike conventional mechanical loading, fire simultaneously modifies the thermal and mechanical properties of construction materials, leading to a progressive deterioration of structural performance. Reinforced concrete (RC) structures are generally considered to possess good fire resistance because concrete is a non-combustible material (Class A1) with relatively low thermal conductivity. Nevertheless, exposure to elevated temperatures causes significant changes in both concrete and reinforcing steel, resulting in reductions in stiffness, strength, and load-bearing capacity. Depending on the fire severity and duration, these changes may be accompanied by cracking, explosive spalling of the concrete cover, excessive deformations, reinforcement buckling, and, in extreme cases, partial or complete structural collapse (Fig. 1).

Figure 1: Examples of fire-damaged RC structural elements

The construction sector is responsible for a substantial share of global material consumption and greenhouse gas emissions, making the preservation and rehabilitation of existing structures an important component of sustainable development. Consequently, reliable methods for evaluating the residual structural capacity of fire-damaged RC structures have become essential for supporting rational engineering decisions. Conservative assessments based solely on visual observations often result in unnecessary demolition, whereas inadequate evaluations may compromise structural safety. An accurate assessment should therefore integrate field investigations, laboratory testing, non-destructive evaluation techniques, and numerical modelling to establish the actual condition and remaining load-bearing capacity of the structure.

The response of reinforced concrete structures to fire is governed by a complex interaction between heat transfer, temperature-dependent material degradation, restraint conditions, and structural behaviour. Concrete experiences dehydration, thermal incompatibility between cement paste and aggregates, and degradation of its mechanical properties, while reinforcing steel loses both strength and stiffness as temperature increases. The severity of damage depends not only on the maximum temperature reached but also on the heating rate, fire duration, cooling conditions, member geometry, moisture content, and loading during fire. Consequently, the evaluation of post-fire structural performance requires a multidisciplinary approach that combines knowledge from structural engineering, materials science, and fire engineering.

This paper presents an overview of the behaviour of reinforced concrete structures subjected to fire, with particular emphasis on methods for assessing residual structural capacity and selecting appropriate repair strategies. The paper discusses the principal mechanisms of fire-induced damage, available assessment techniques, and commonly adopted rehabilitation measures. To demonstrate the practical application of these procedures, a detailed case study involving the investigation, numerical assessment, and repair of a fire-damaged reinforced concrete building is presented. The study illustrates how the integration of experimental observations and numerical analysis can support reliable decisions regarding structural rehabilitation and contribute to the sustainable reuse of damaged structure.

2. BEHAVIOUR OF REINFORCED CONCRETE STRUCTURES UNDER FIRE

The response of reinforced concrete (RC) structures to fire is governed by the coupled effects of heat transfer, temperature-dependent material degradation, and structural loading. Unlike ordinary mechanical actions, fire produces continuously changing thermal conditions that alter the physical and mechanical properties of both concrete and reinforcing steel. Consequently, the structural response evolves throughout the heating and cooling phases, making fire a highly complex loading scenario.

The thermal exposure of a structure depends on the characteristics of the fire, including the type and quantity of combustible materials, ventilation conditions, enclosure geometry, and fire duration. In structural fire engineering, the standard ISO 834 temperature-time curve is commonly adopted for design purposes because it provides a uniform basis for evaluating fire resistance. However, real fires rarely follow this idealized temperature development. Natural fires generally consist of ignition, growth, fully developed, and decay phases, with peak temperatures and heating rates that depend on the fire load and ventilation conditions. Therefore, realistic fire scenarios should be considered whenever the residual performance of fire-damaged structures is assessed.

Concrete is inherently non-combustible and possesses relatively low thermal conductivity, which delays heat penetration into structural members and provides natural protection for embedded reinforcement. Nevertheless, increasing temperature induces a series of physical and chemical transformations within the concrete matrix. Moisture evaporation, dehydration of cement hydrates, differential thermal expansion between aggregates and cement paste, and the decomposition of hydration products lead to progressive reductions in compressive strength, elastic modulus, and stiffness. At temperatures exceeding approximately 300–400 °C, mechanical degradation becomes increasingly significant, while temperatures above 600 °C may result in severe deterioration of concrete properties. The extent of damage depends on several factors, including aggregate type, moisture content, permeability, heating rate, and cooling conditions.

One of the most critical phenomena associated with fire exposure is explosive spalling of concrete. Spalling may occur when pore pressure generated by evaporating moisture combines with thermally induced stresses, causing sudden detachment of the concrete cover. This phenomenon reduces the effective cross-sectional area of structural members and exposes reinforcing steel directly to fire, thereby accelerating temperature rise within the reinforcement. High-strength concrete is generally more susceptible to explosive spalling because of its lower permeability, whereas the incorporation of polypropylene fibres has proven effective in reducing this risk by providing additional pathways for vapour pressure dissipation.

The mechanical properties of reinforcing steel are also strongly influenced by elevated temperatures. Although steel has a much higher thermal conductivity than concrete, it is initially protected by the surrounding concrete cover. As temperature increases, however, both the yield strength and elastic modulus decrease progressively, resulting in reduced stiffness and load-bearing capacity. Thermal expansion of reinforcement, combined with restraint imposed by surrounding concrete, generates additional internal stresses that may contribute to cracking, reinforcement buckling, and excessive structural deformations. During prolonged fire exposure, these effects may significantly alter the internal force distribution within statically indeterminate structures.

The structural response of reinforced concrete members during fire is therefore governed by the interaction between thermal gradients, material degradation, and mechanical loading. Depending on the fire scenario and structural configuration, the observed damage may include surface discoloration, cracking, delamination, spalling, reinforcement exposure, excessive deflections, and local or global collapse (Fig. 1).

However, the visible extent of damage does not necessarily reflect the residual load-bearing capacity of the structure. Consequently, reliable post-fire assessment requires a comprehensive evaluation that combines visual observations with experimental investigations and numerical analysis to determine the actual condition of the structural system.

3. POST-FIRE ASSESSMENT OF REINFORCED CONCRETE STRUCTURES

Fire exposure can significantly affect the condition, stability, and load-bearing capacity of structural elements. After a fire, it is therefore necessary to determine the residual bearing capacity of the structure and to assess whether it can safely remain in service.

The assessment of reinforced concrete structures after fire exposure represents one of the most challenging tasks in structural engineering. Unlike conventional structural damage, fire-induced deterioration is often highly non-uniform, with significant variations in temperature distribution both across the cross-section of individual members and throughout the structural system. Moreover, the actual fire scenario is frequently unknown, making it difficult to estimate the maximum temperatures reached and the duration of thermal exposure.

All these factors lead to the conclusion that the assessment should be performed systematically, starting with an initial inspection and continuing with a detailed investigation and structural analysis. Based on the results obtained, an appropriate decision can then be made regarding repair, strengthening, partial replacement, or demolition. The post-fire investigation workflow presented in Fig. 2 is divided into three main stages: initial assessment, detailed investigation, and final decision.

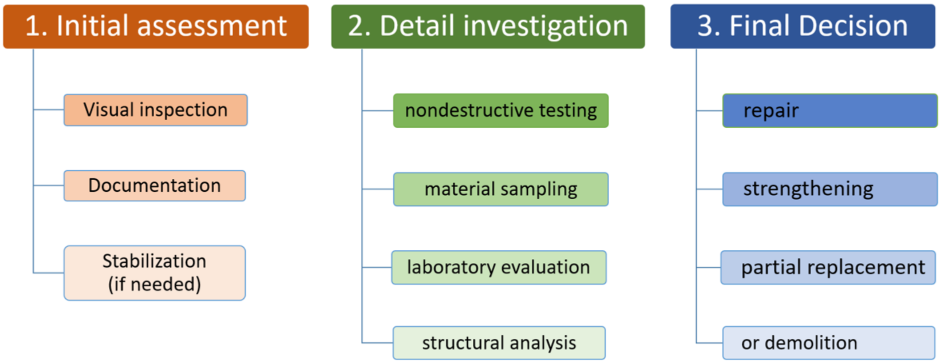

Figure 2: Post-Fire Investigation Workflow

3.1. INITIAL ASSESSMENT

The first stage of the post-fire investigation is the initial assessment of the structure. This stage begins with a detailed visual inspection aimed at identifying visible signs of fire damage. Important indicators include crack patterns, spalling depth, reinforcement exposure, deformation, and discoloration. These observations provide an initial indication of the severity and distribution of the damage.

Crack patterns can provide information about possible damage to concrete and structural elements, while the depth of spalling can indicate the extent to which the concrete surface and protective layers have been affected. Particular attention should also be paid to exposed reinforcement, since fire exposure can affect the condition and performance of both concrete and reinforcement. Deformations may indicate changes in the structural geometry or possible loss of stiffness, while discoloration can provide additional visual evidence of thermal exposure.

The findings from the visual inspection should be carefully documented. This includes recording the observed damage, taking photographs, collecting available drawings, and gathering other relevant information about the structure. Proper documentation is important because it provides the basis for the subsequent investigation and structural assessment.

If the structure presents a safety risk, stabilization measures may be required before further investigation is carried out. These measures are intended to ensure safety and prevent further damage or possible collapse.

3.2. DETAILED INVESTIGATION

Following the initial assessment, a detailed investigation is performed. According to the presented workflow, this phase includes non-destructive testing, material sampling, laboratory evaluation, and structural analysis.

Non-destructive testing is used to obtain additional information about the condition of the structure without causing significant damage to the investigated elements. These methods can identify internal cracking, voids, delamination, and damaged regions that may not be visible during a conventional visual inspection. This makes non-destructive testing an important part of the assessment of fire-damaged structures.

The next step is material sampling. Representative samples of concrete, steel, and other relevant materials can be collected and examined. Laboratory testing provides information about important material properties, including compressive strength, stiffness, permeability, and microstructural damage.

The laboratory results complement the information obtained through visual inspection and non-destructive testing. They provide a more detailed understanding of how fire exposure has affected the material properties. This information is particularly important when determining the remaining capacity of structural elements.

The final part of the detailed investigation is structural analysis. The purpose of the analysis is to evaluate the remaining capacity and structural performance under current and future loads. By combining the results from the different investigation methods, engineers can develop a more reliable assessment of the actual condition of the structure and determine whether its residual bearing capacity is sufficient.

3.3. FINAL DECISION AND REPAIR STRATEGIES

After completing the investigation and structural analysis, the final stage is the decision phase. At this point, engineers select the most appropriate strategy based on the severity of the damage and the remaining structural capacity. The possible solutions presented in the slides include repair, strengthening, partial replacement, or demolition.

For moderate fire damage, surface and local repair methods can be applied. These include patch repair, shotcrete, crack injection, and replacement of damaged cover concrete. An important aspect of these repair methods is proper surface preparation. Adequate surface preparation is necessary to achieve good bond quality between the existing and new materials and to ensure satisfactory long-term performance.

When the existing structural capacity is insufficient, structural strengthening may be required. The presented methods include reinforced concrete jacketing, steel jacketing, FRP strengthening, and external post-tensioning. The selection of the appropriate strengthening method depends on several factors, including the severity of the damage, the structural configuration, the level of fire exposure, and the future performance requirements of the structure.

In some cases, only a limited part of the structure may be severely damaged. In such situations, partial replacement of damaged elements can be considered instead of repairing or replacing the entire structure. However, if the investigation shows that the structure has suffered extensive damage and that safe restoration is not feasible, demolition may be necessary.

Overall, the assessment of residual bearing capacity after a fire should be understood as a systematic engineering process rather than a single inspection or test. The combination of visual inspection, documentation, non-destructive testing, material sampling, laboratory evaluation, and structural analysis provides a sound basis for selecting the appropriate intervention. The final objective is to ensure that any decision concerning continued use, repair, strengthening, partial replacement, or demolition is based on the actual condition and performance of the structure. The slides also emphasize that safety is paramount throughout the entire process, and that the assessment and subsequent measures should comply with applicable codes, standards, and guidelines.

4. CASE STUDY: POST-FIRE ASSESSMENT AND REHABILITATION OF A REINFORCED CONCRETE RESIDENTIAL BUILDING

A representative case study of post-fire structural assessment and rehabilitation is the residential building located in Skopje. On 1 December 2017, a fire occurred in the basement of the building and affected approximately one third of the basement area (Fig. 3). The affected space was used as a storage area containing combustible material with a high fire load. Due to the limited ventilation and the large amount of combustible material, the fire developed slowly and lasted for several hours. According to the temperature measurements recorded by the firefighters, temperatures exceeding 1000 °C were locally reached within the fire-affected zone. After the fire was extinguished, visible damage to several structural elements was observed, parts of the structure were temporarily supported, and the building was taken out of service.

The existing structure is a reinforced-concrete spatial frame system consisting of beams, columns and reinforced-concrete walls. The floor slabs are reinforced in two directions and have a thickness of 14 cm, while the main beams and columns in the investigated area have dimensions of approximately 25/50 cm and 25/60 cm, respectively. The original structural elements were designed using MB30 concrete and RA 400/500-2 reinforcement.

4.1. INITIAL ASSESSMENT AND DAMAGE DOCUMENTATION

The first stage of the investigation consisted of a detailed visual inspection and documentation of the fire damage. Several different levels of damage were identified. The most severe damage was observed in one reinforced-concrete floor slab, where complete degradation of the concrete and collapse of the slab occurred (Fig. 4). In adjacent areas, extensive spalling of the concrete cover was observed (Fig. 5). Other elements showed changes in concrete colour, surface cracking, partial loss of the protective concrete layer and deposits of smoke and soot.

The damage was not uniform throughout the structure. Some slabs had mainly smoke and soot deposits without visible cracking or spalling, while columns such as C2 and C3 exhibited surface microcracking and changes in concrete colour but no significant loss of the protective layer.

Column C4 showed mainly a change in surface colour without visible surface cracking. This variation in damage was important for determining which elements required complete replacement and which could be rehabilitated.

As an immediate safety measure, damaged structural elements were supported before the detailed investigation. This corresponds to the initial stabilization stage of a typical post-fire assessment procedure.

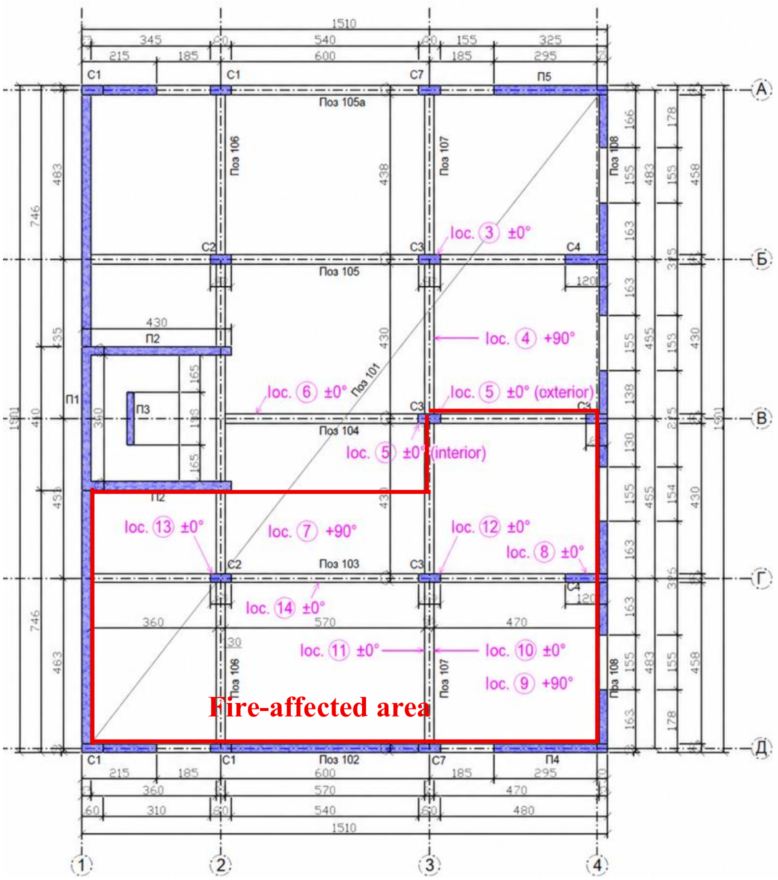

Figure 3: Basement floor plan showing the fire-affected area and locations of non-destructive testing

Figure 4: Complete degradation of the concrete and collapse of the RC floor slab between Axes 2 and 3

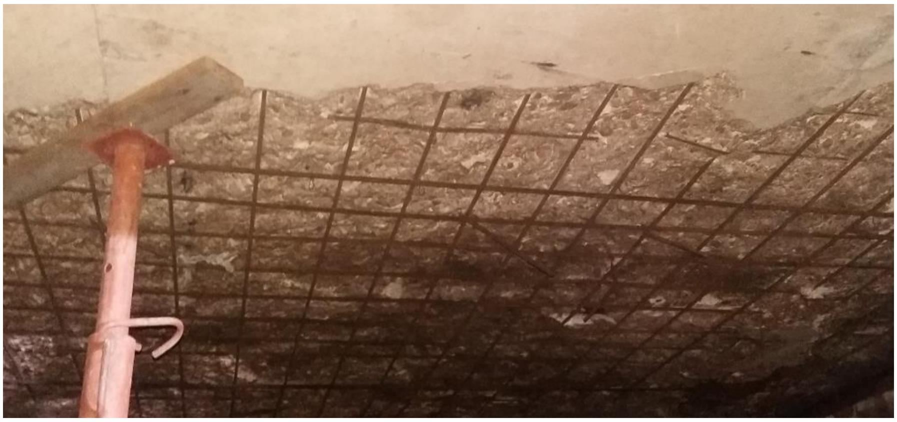

Figure 5: Extensive spalling of the concrete cover of the RC floor slab between Axes 1 and 2

4.2. INVESTIGATION AND ASSESSMENT OF RESIDUAL CAPACITY

After the visual inspection, non-destructive testing was carried out to obtain additional information about the condition and strength of the concrete. A Schmidt hammer was used to estimate the compressive strength of the concrete at 14 measurement locations (Fig. 3), including slabs, beams, columns and reinforced-concrete walls. The measured results showed differences between the investigated locations, which helped identify areas with more pronounced fire effects and provided additional information for the structural assessment.

However, the assessment was not based only on visual observations and measurements. Because high temperatures can significantly reduce the mechanical and stiffness properties of concrete and reinforcement, a combined thermal and structural analysis was performed. The reinforced-concrete frame designated as Frame G, which had experienced significant visible damage, was selected for detailed analysis. The analysis was performed using the SAFIR software, specifically developed for thermal and structural analysis of fire-exposed structures.

Based on the fire conditions, including the fire load density and ventilation factor, and taking into account the temperatures measured by the firefighters, the fire was modelled using the ISO 834 standard temperature–time curve. The analysis considered temperature-dependent thermal and mechanical properties of concrete and steel in accordance with Eurocode 2, Part 1-2.

The numerical analysis indicated a calculated fire resistance period of approximately 2.8 hours for the investigated frame. Failure in the model occurred due to the formation of a plastic hinge in the middle span. The beams survived the fire exposure but experienced visible damage and plastic deformations associated with yielding of the reinforcement. Importantly, the analytical results were consistent with the damage observed during the site inspection. The 500°C isotherm was located approximately 3–4 cm below the exposed surface (Fig. 6), indicating that a significant part of the concrete cross-section retained its initial load-bearing capacity. This conclusion was also consistent with the Schmidt hammer measurements.

4.3. REHABILITATION STRATEGY

Based on the combined visual inspection, measurements and thermal-structural analysis, a targeted rehabilitation strategy was selected rather than complete demolition of the structure. Elements with severe and clearly visible damage were assigned complete replacement, while elements with residual capacity were rehabilitated or strengthened (Fig.7).

The severely damaged floor slab was removed and replaced with a new 14 cm thick reinforced-concrete slab. The existing reinforcement that remained suitable was incorporated into the new structural system, while additional reinforcement was provided in both directions.

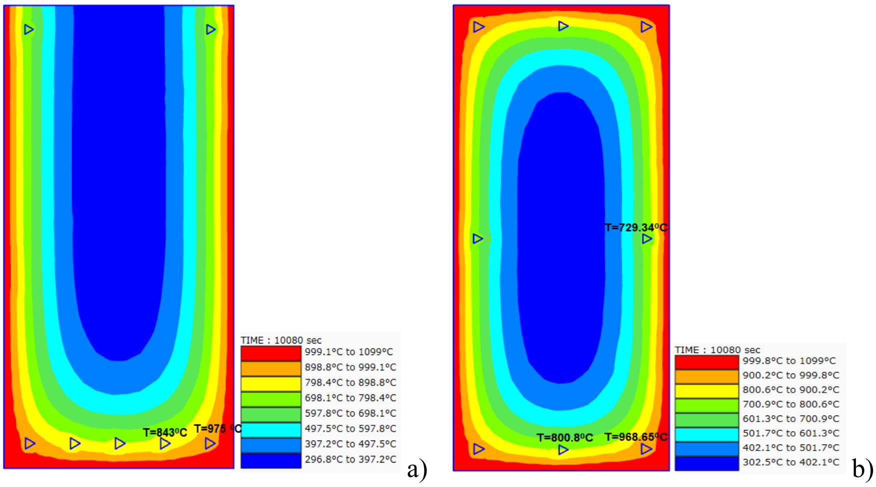

Figure 6: Isotherms in the cross sections of a) beam b) column, at moment t=2,8 hours

Figure 7: Repair and strengthening of fire damaged RC structural elements

For partially damaged slab areas, the degraded concrete cover was removed, anchors and additional reinforcement were installed, and a new concrete layer was applied using shotcrete. Similar rehabilitation was specified for the damaged basement reinforced-concrete walls.

The columns C2 and C3 were strengthened by increasing their cross-sectional dimensions and adding new reinforcement. The existing columns were enlarged with a new reinforced-concrete layer, while the connection with the existing foundation was achieved using anchored reinforcement.

The damaged beams were rehabilitated by increasing their cross-section on three sides. New reinforced-concrete portions were added parallel to the existing beams and connected to the existing structure using anchors and stirrups. Following the strengthening, the beam cross-section was increased to approximately 50/55 cm.

This case demonstrates a complete and practical post-fire structural assessment workflow. The procedure began with securing and visually inspecting the damaged structure, followed by systematic documentation and non-destructive testing. The residual structural capacity was then evaluated through a combination of experimental measurements and numerical thermal-structural analysis. Finally, the results were used to distinguish between elements requiring complete replacement and those suitable for repair or strengthening.

The main principle of the rehabilitation was therefore not to replace the entire structure, but to restore the required structural capacity by applying appropriate measures according to the actual level of damage. The combination of slab replacement, local concrete repair, shotcrete, additional reinforcement and enlargement of beams and columns allowed the damaged structural system to be returned towards its original mechanical capacity. The case therefore represents a good example of how a systematic post-fire investigation can lead to a technically justified and targeted rehabilitation strategy.

5. CONCLUSIONS

Fire exposure may significantly impair the structural performance of reinforced concrete members despite the non-combustible nature and inherent fire resistance of concrete. Reliable evaluation of fire-damaged structures therefore requires a comprehensive assessment of both concrete and reinforcing steel before decisions regarding repair or demolition are made.

The following conclusions can be drawn from this study:

1. Visual inspection provides essential preliminary information but is insufficient for evaluating the residual structural capacity of fire-damaged reinforced concrete structures. Reliable assessment requires the integration of field observations with laboratory investigations and numerical analyses.
2. Experimental testing and thermo-mechanical numerical modelling complement each other in estimating the residual mechanical properties of structural members. Their combined application significantly reduces uncertainty in evaluating the remaining load-bearing capacity.
3. The presented case study demonstrated that severe visible fire damage does not necessarily imply loss of structural safety. Although extensive cracking, discoloration, and local spalling were observed, the integrated assessment confirmed that a substantial portion of the structural capacity had been preserved.
4. A rehabilitation strategy based on quantified residual capacity enables targeted strengthening of only the critically damaged structural members. This approach improves structural safety while avoiding unnecessary demolition and reconstruction.
5. Repair and rehabilitation should be regarded as sustainable engineering solutions whenever technically feasible. Comprehensive post-fire assessment supports informed decision-making, extends the service life of existing structures, reduces construction waste, and contributes to more sustainable management of the built environment.

The presented methodology demonstrates that combining inspection, experimental investigation, and advanced numerical analysis provides a reliable basis for post-fire assessment and rehabilitation of reinforced concrete structures. Such integrated engineering approaches are expected to play an increasingly important role as resilience and sustainability become central objectives in structural design and asset management.

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