State-of-the-art review on the post-fire assessment of concrete structures

Balša Jovanović [a,b], Robby Caspeele [a], Geert Lombaert [b], Edwin Reynders [b] , Ruben Van Coile [a]

[a] *Ghent University, Department of Structural Engineering and Building Materials, Ghent, Belgium*
[b] *KU Leuven, Department of Civil Engineering, Leuven, Belgium*

Corresponding Author: Balsa.Jovanovic@ugent.be

Fires are rare events, but in the case of their occurrence they can have a significant effect on the structure. Concrete is a durable non-combustible material but can be damaged by fire. This damage does not often lead to structural collapse, but can significantly hinder the structure's future performance. A thorough post-fire assessment of concrete structures is essential to determine the condition of the structure and select the best course of action to take. This paper reviews the current state of knowledge on the post-fire assessment of concrete structures. The techniques that are commonly used are presented and discussed, highlighting their advantages and disadvantages. Furthermore, based on the literature case studies, an overview of different approaches and techniques is presented. Finally, the framework and goals of the post-fire assessment are investigated. The paper concludes with a summary of the current state of knowledge and a list of key research needs.

1 Introduction

Even though the fire occurrence probability is low, there is no way to completely eliminate it. Fire can occur at any point in time, for example during the construction phase like Windsor Tower in Madrid in 2005, or during normal use like in the case of the 2017 Grenfell Tower fire. Fire can be triggered by a multitude of factors ranging from terrorist attacks (World Trade Centre in 2001) to an electrical short circuit in a coffee machine (Delft Architectural

Postprint submitted to Structural Concrete
Published version: B. Jovanović, R. Caspeele, G. Lombaert, E. Reynders, and R. Van Coile. State-of-the-art review on the post-fire assessmentof concrete structures. *Structural Concrete*, 24(4):5370-5387, 2023. https://doi.org/10.1002/suco.202201108 .

Engineering School building in 2008). Similarly, its effects on the structure can range from insignificant soot marks on walls to full collapse.

The complete collapse of structural systems due to fire is a rare event (Beitel and Iwankiw, 2005). Nevertheless, the structure usually does not survive fire undamaged (CIB W14 Report, 1990). Building materials tend to lose their strength when exposed to elevated temperatures. This, together with additional thermal effects, can cause damage to the structure that can often be hard to detect and quantify. However, it is of utmost importance to properly assess it, as that information is needed to ensure adequate safety and serviceability of a structure (Molkens *et al.*, 2017).

Concrete members are, due to their dimensions and material properties, highly resilient to fire damage and usually survive most fire exposures (Kodur, 2014). For that reason, the assessment of their post-fire condition is important. Due to the complexity of both concrete as a material and fire as a phenomenon, there is a wide range of effects and damage after a fire (Taerwe *et al.*, 2008). This, in turn, is a reason why there is currently no widespread standardized way of conducting a post-fire assessment of concrete structures.

This article first shortly presents what effects a fire can have on reinforced concrete structures. Then, building on that, the goals of structural post-fire assessment are discussed and formulated and it is identified which observations and measurements are crucial for a proper assessment. Afterwards, different techniques used in practice are examined together with their advantages and disadvantages. Furthermore, different methods of assessing the residual condition and capacity of a fire-damaged structure are presented. Finally, evaluation and intervention strategies found in the literature are presented and discussed.

2 Fire damage to concrete structures

To be able to properly assess the condition of concrete structures after a fire, the mechanism and types of damage a fire can cause have to be discussed. Concrete is a complex heterogeneous material that can be simply described as consisting of two parts, the aggregates and a cement matrix that binds them. Most of the damage in concrete structures can be attributed to the physical and chemical changes of either of these two parts or their bond (fib Fédération International du Béton, 2007).

The cement matrix presents the binding agent of the concrete and its behaviour is the main reason for the change of the concrete characteristics in case of fire. During the heating, cement goes through a few stages of physical and chemical changes losing its strength along the way. This is in contrast with the aggregates, which are thermally stable up until temperatures of 500 °C and mostly only exhibit thermal expansion. However, as the cement matrix starts shrinking at temperatures above 100 °C, an incompatibility between the matrix and the aggregates occurs. This incompatibility causes cracking in the bond zone between the aggregates and the cement and therefore leads to a substantial loss of strength. These cracks, combined with the degradation of the cement paste are the biggest driver for the reduction of the strength of concrete at elevated temperatures (fib Fédération International du Béton, 2007).

This reduction of strength has been the focus of previous investigations, e.g.(Khoury, 1996; Lie and Kodur, 1996; Kakae *et al.*, 2017). These investigations indicate that there are two components to the strength reduction, one as a result of the heating and an additional one as a result of the post-fire cooling of concrete (Li and Franssen, 2011). There are however large uncertainties when considering these reductions. (Qureshi *et al.*, 2020) suggested probabilistic models for the heating phase, while (Shahraki *et al.*, 2022) developed probabilistic models for the residual compressive strength. A common reference with respect to the strength reduction during the heating of concrete is the proposal included in EN 1992-1-2:2004 (CEN, 2004), while EN 1994-1-2:2005 (CEN, 2005) specifies an additional 10% reduction of strength to take into account the subsequent cooling effects.

Fire damage is not limited only to concrete, it can also affect the reinforcement steel. The reinforcement can be damaged in two ways. Firstly, its mechanical properties can be reduced due to the elevated temperatures it experiences. Luckily, in contrast with concrete, almost all of this reduction is recoverable after cooling if it was exposed to temperatures lower than 500-600 °C and at least a part of it is recoverable for higher temperatures (Neves *et al.*, 1996). The second damage type is the degradation of the bond between the reinforcement and the cement matrix. The effects of this on the member's capacity are limited (Kodur and Agrawal, 2017).

Due to the thermal properties of concrete, the thermal gradient inside of concrete during the fire is highly nonuniform in most cases. This, coupled with the thermal elongation and the fact that plane sections remain plane, can cause internal compatibility stresses (Van Coile *et al.*, 2014a). This is illustrated in Figure 1 for the case of a reinforced concrete slab exposed to fire from the bottom side, where ε_c represents the strain in the top concrete fiber and ε_s in the bottom reinforcement. Because parts of the strains induced during the heating are irreversible (a combination of both plastic and irreversible load-induced transient strains), these internal compatibility stresses can be present in some form in the structure after the cooling and therefore highly influence the maximum loads the structure can handle. Furthermore, due to the nonuniform thermal gradient and reduction of the strength at elevated temperatures, an even steeper damage gradient often occurs in the concrete.

Due to its composition, material behaviour and innate porosity, concrete as a structural material exhibits spalling at elevated temperatures. It is the violent or non-violent breaking off of layers or pieces of concrete from the surface of a structural member when it is heated rapidly to high temperatures (Khoury, 2000). It can have a significant negative effect on the structure, as it can partially or completely remove the protective concrete cover and, in that way, more directly expose reinforcement to the fire exposure. Furthermore, it can change the shape of the cross-section and in that way reduce its capacity or even shift the centroid which can cause dangerous 2nd order effects in some cases. Unfortunately, the mechanisms leading to spalling are still not fully understood and remain the focus of a lot of research. However, the main influencing factors have been identified as heating rate, permeability of the material, pore saturation level, the presence of reinforcement and the level of the externally applied load (Khoury, 2000). Examples of spalling on reinforced concrete beams and columns are presented in Figure 2, showing how it can cause a significant reduction of the cross-section.

The effect fire can have on the concrete structure is complex. The damage occurs both on the material and structural levels. Loads, stiffnesses, geometry and capacity change during the heating and oftentimes during the cooling of the structure too. For these reasons, post-fire assessment is not a straightforward procedure. The damage must be evaluated on both local and global levels and a series of different techniques must be employed in order to properly estimate the damage and future performance of the whole structure

3 Post-fire assessment of concrete structures

3.1 Goal

Stochino *et al.,* (2017) state that the post-fire assessment goal is quantifying the extent and gravity of fire damage in order to plan the rehabilitation or the demolition. According to Alonso, (2008) post-fire assessment is needed in order to identify the level of damage, and the residual structural capacity has to be accurately addressed in order to define the best strategy for repairing or to decide on demolition. Similar definitions with some modifications are found throughout the literature, but in most case studies it is in essence agreed that post-fire assessment should determine the condition of the structure and decide if it is safe for future use.

3.2 Assessment framework

Similarly, as for the goal, there is no commonly accepted framework for the execution of the post-fire assessment. Multiple authors provided their suggestions as to what the framework should look like. Stochino *et al.*, (2017) propose an assessment framework that essentially consists of two parts: firstly detecting geometrical variations, due to thermal deformation and secondly detecting degradation of the mechanical characteristics of materials. Furthermore, the authors state that the second part must be integrated with the reconstruction of the temperature-time history experienced by the structure. Finally, they state that assessment techniques should be combined and refined by theoretical and numerical thermo-mechanical modelling.

The framework by Stochino *et al.*, (2017) however does not provide guidance on the sequence of use or combination of assessment techniques. Such guidance is included in the frameworks proposed by Osman *et al.*, (2017) and Srinivasan *et al.*, (2014). Specifically, Osman *et al.*, (2017) present a simple assessment framework where the first step is to conduct a visual inspection. Then, based on the results of the inspection, the next steps are to plan and conduct non-destructive and destructive tests, which should finally be used for the structural analysis.

A much more detailed framework for the post-fire assessment is proposed in Srinivasan *et al.*, (2014). The framework starts with a preliminary visual inspection where, basic information such as the source of the fire and the location of the damage should be determined. It is followed by a detailed investigation which includes fire severity estimation, damage categorization and use of both non-destructive and destructive techniques. Lastly, based on the detailed investigation, assessment and classification of the damage should be conducted. Although it predates the framework by Srinivasan, the framework by (Gosain *et al.*, 2008) in effect provides an extension to the above in that it similarly suggests preliminary inspection, followed by a detailed inspection and structural analysis. However, the authors add another step at the end, development of a repair strategy, which consists of evaluating the options, selecting the repair materials and detailing the repairs.

Some authors recommend that the focus should be more on the residual capacity than on the damage detection and classification. Molkens *et al.*, (2017) suggest a five-step assessment consisting of on-site inspection, informed assessment of fire severity, residual capacity determination, a decision on the intended continued use and a repair strategy. Kodur and Agrawal, (2021) also proposed a five-step framework, this time consisting of determining the fire exposure, determining the peak temperatures experienced at exposed surfaces, damage classification, estimation of the residual mechanical properties and finally residual capacity evaluation based on which a final repair decision is made. Both frameworks highlight that a decision of how the structure is going to be rehabilitated should be based on its residual capacity.

Table 1 Steps included in the post-fire assessment framework proposed in the literature

	Inspection	**Fire severity assessment**	**Damage classification**	**Residual capacity**	**Repair**
(Stochino et al., 2017)	✓	✓	✓/✗	✗	✗
(Osman et al., 2017)	✓	✗	✗	✓	✗
(Srinivasan et al., 2014)	✓	✓/✗	✓	✓	✗
(Gosain *et al.*, 2008)	✓	✗	✓	✓	✓
(Molkens et al., 2017)	✓	✓	✗	✓	✓
(Kodur and Agrawal, 2021)	✓	✓	✓	✓	✓

Based on this review of assessment frameworks, Table 1 summarizes which steps have been included in different proposed post-fire assessment frameworks. Furthermore, it is concluded that the existing studies agree that the first and most basic step of the assessment is to determine if the structural elements and/or system were actually damaged by the fire. Each part of the structure is usually visually inspected in order to understand if the fire damage is more serious than cosmetic or superficial. In the case of only superficial damage, most authors agree that members can be considered safe for future use. In contrast to the situation of superficial damage, severe fire damage can be evident, which leads to demolition as the only option. The engineering-wise most interesting cases are those where the fire damage is more severe than superficial but it is not evidently non-repairable. Then the main focus of the post-fire assessment becomes determining the extent of the damage. It should be noted that a preliminary inspection is recommended in order to detect whether the immediate safety issues of the structure exist and whether quick actions are needed. This preliminary assessment can be considered as a part of the visual inspection.

The reviewed studies agree that the most important aspect when assessing the safety of a structure post-fire is to evaluate the residual capacity of its members. For that reason, a few structural characteristics that can be affected by the fire must be determined. One highly important and the most often assessed is the compressive strength of concrete, or more precisely its residual strength after the fire exposure (Peker and Pekmezci, 2002; Folic *et al.*, 2002; Stawiski, 2006; Kose *et al.*, 2006; Dilek, 2007; Gosain *et al.*, 2008; Epasto *et al.*, 2010; Jansson *et al.*, 2011; Srinivasan *et al.*, 2014; Ha *et al.*, 2016; Osman *et al.*, 2017; Stochino *et al.*, 2017; Wijaya, 2018; Aseem *et al.*, 2019; Knyziak *et al.*, 2019; Ali Musmar, 2020; Wróblewski and Stawiski, 2020). A wide range of techniques, both non-destructive and destructive, are used to assess the residual compressive strength of concrete.

The second most important characteristic is the residual strength of the reinforcement. In practice, its assessment is not common but numerous authors have used it in their assessments (Kose *et al.*, 2006; Gosain *et al.*, 2008; Ha *et al.*, 2016; Khiyon *et al.*, 2017; Stochino *et al.*, 2017). Compared to the concrete strength, only destructive methods are available to measure it, explaining why the direct post-fire assessment of reinforcement strength is not commonly executed. However, it is highly important, especially for reinforced concrete (RC) members exposed to bending action.

Finally, residual deflections are another important characteristic, but are quite often overlooked and are rarely the focus of the assessment. The few identified studies that assign large importance to the assessment of residual deflections are (Molkens *et al.*, 2017; Stochino *et al.*, 2017). Residual deformations can have a significant effect on the behaviour of RC members as they can cause significant 2nd order effects. Furthermore, these deformations can also be used as indirect information about the degradation of other mentioned parameters.

Based on these parameters, the damage level of the structure can be properly assessed. The last step in the post-fire assessment is determining if the structure is safe enough for continued use. After all, normal variations in loads throughout the (remaining) life of the structure imply that it is not sufficient to look at the structure's stability immediately after the fire to conclude that stability will be maintained in years to come. Furthermore, the uncertainty of the fire exposure experienced by the structure and the residual properties implies that there is also considerable uncertainty with respect to the residual capacity of the structure. In structural engineering for normal design conditions, the stochastic nature of the loads and the uncertainty on the resistance are explicitly taken into account through safety factors aimed at achieving a target reliability index (i..e, a maximum failure probability). If the safety is not ensured, then one of three options should be considered: change of the function and use of the structure to meet the safety criteria, repair or demolition.

3.3 Conclusions on the post-fire assessment goal and framework

The post-fire assessment's purpose is to examine the condition of the structure after the fire and determine if it is safe to be used in the same way as before the fire or if a modification of the structure and/or its use is needed. It should contain the following three steps:

1. Damage detection and identification - determine which parts of the structure have experienced significant damage, then determine the extent and type of that damage
2. Residual performance evaluation - determine how the damage influences the structure's safety
3. Evaluation and intervention strategy– recommend what is the best course of action, cognisant of the residual safety evaluation.

4 Damage assessment techniques

The techniques used for post-fire assessment of concrete structures can roughly be separated into three categories: Non-Destructive, Destructive and Numerical.

4.1 Non-destructive techniques

Non-Destructive Techniques (NDT), as their name suggests, leave no or insignificant damage to the structure after their use. While it is their biggest advantage compared to destructive techniques, it is also their biggest limitation, however. It has already been highlighted that one of the most important pieces of information to be evaluated through the post-fire assessment is the residual capacity of a member and therefore, the residual strength of the materials. The only way to directly measure the strength is to load at least a sample of material until it fails. Because of this, it is impossible to directly measure residual strength in a non-destructive way, it can only be done indirectly, using previously determined correlation.

4.1.1 Visual inspection

The most simple, but also the most essential NDT is the visual inspection. The term visual inspection consists of optical inspection but is often paired with simple sound techniques like hand or hammer tapping (Chew, 1993). Visual inspection allows a wide range of damage detection, from detecting parts of the structure completely unaffected by the fire, to parts that are beyond repair (Chew, 1993). With it, damage like spalling or exposed rebar buckling can also be easily spotted. However, there are limitations to the visual inspection. Most importantly it can provide information on the material condition through the depth only in cases where there is visible damage, or if, for instance, a dull sound occurs when the member is tapped (Chew, 1993). Furthermore, the results of visual inspection can often be quite descriptive and subjective, the damage and strength reduction can be detected but not quantified. Exceptions to this are residual deformations which can be measured with high precision.

Visual inspection can also provide the location of the fire and even provide an idea of its intensity. By looking at the damage (or lack of damage) to the other materials in the building, a rough idea of the maximum temperature during the fire can be obtained (Table 2), as highlighted by (Kodur and Agrawal, 2021). For example, completely melted aluminium indicates that the temperature in the compartment reached at least 600 °C (melting point of aluminium). This approach was implemented in a large number of studies (Folic *et al.*, 2002; Kose *et al.*, 2006; Alonso, 2008; Gosain *et al.*, 2008; Srinivasan *et al.*, 2014; Molkens *et al.*, 2017; Aseem *et al.*, 2019; Knyziak *et al.*, 2019; Ali Musmar, 2020; Wróblewski and Stawiski, 2020) with varying degrees of detail.

Table 2 Assessment of temperature reached by selected materials and components in fires (Kodur and Agrawal, 2021)

Substance	Typical examples	Conditions	Approx. Temp. (°c)
Paint	—	Deteriorates	100
		Destroyed	150
Polystyrene	Thin-wall food containers, foam, light shades, handles, curtain hooks, radio casings	Collapse	120
		Softens	120–140
		Melts and flows	150–180
Polyethylene	Bags, films, bottles, buckets, pipes	Shrivels	120
		Softens and melts	120–140
Polymethylmethacrylate	Handles, covers, skylights, glazing	Softens	130–200
		Bubbles	250
PVC	Cables, pipes, ducts, linings, Profiles, handles, knobs, houseware, toys, bottles	Degrades	100
		Fumes	150
		Browns	200
		Charring	400–500
Cellulose	Wood, paper, cotton	Darkens	200–300
Wood	—	Ignites	240
Solder lead		Melts	250

	Plumber joints, plumbing, sanitary installations, toys	Melts, sharp edges rounded	300–350
		Drop formation	350–400
Zinc	Sanitary installations, gutters, downpipes	Drop formations	400
		Melts	420
Aluminium and alloys	Fixtures, casings, brackets, small mechanical parts	Softens	400
		Melts	600
		Drop formation	650
Glass	Glazing, bottles	Softens, sharp edges rounded	500–600
		Flowing easily, viscous	800
Silver	Jewellery, spoons, cutlery	Melts	900
		Drop formation	950
Brass	Locks, taps, door handles, clasps	Melt (particularly edges)	900–1000
		Drop formation	950–1050
Bronze	Windows, fittings, doorbells, ornamentation	Edges rounded	900
		Drop formation	900–1000
Copper	Wiring, cables, ornaments	Melts	1000–1100
Cast iron	Radiators, pipes	Melts	1100–1200
		Drop formation	1150–1250

4.1.2 Surface hardness

An NDT that is quite often used both in regular and post-fire concrete assessment is measuring surface hardness using a rebound (Schmitt's) hammer. Even though this technique does not directly measure the compressive strength of concrete there is a lot of evidence of a strong correlation between the compressive strength and measured surface hardness (Breysse, 2012b). However, these correlations have to be used with great care, as they are affected by a lot of factors such as concrete type, mixture, moisture level, presence of reinforcement etc (Bungey and Millard, 1995).

The surface hardness methods are employed in post-fire assessment in multiple ways, most notably to localize the parts of the structure that experienced fire damage (Chew, 1993) and to obtain the residual strength of the concrete (Aseem *et al.*, 2019). It should be noted that estimating the concrete compressive strength based on the surface hardness can be dangerous. As stated and applied in (Colombo and Felicetti, 2007), (Cioni *et al.*, 2001), (Awoyera *et al.*, 2014) and (Gosain *et al.*, 2008) this technique should only be used for damage detection, because it can provide information only on the limited depth of concrete and the correlation between the strength and measurements can depend on numerous uncertain factors.

When used for damage detection, the surface hardness evaluation can be very efficient. The places of the structure where the surface hardness is significantly lower suggest a higher degree of fire damage. The rebound hammer is quite fast and easy to operate making it useful to quickly map the locations of damage in large areas. In order to quantify the damage at these locations, other better-suited techniques should then be used.

Despite that, some studies like (Ali Musmar, 2020) and (Aseem *et al.*, 2019) use surface hardness measurements to explicitly obtain the concrete compressive strength. In the case of (Ali Musmar, 2020), however, the authors did not explicitly specify which correlation was used to obtain it. On the other hand, (Aseem *et al.*, 2019) used core samples to obtain the relationship between the rebound number and the compressive strength. Also, the determination of a correlation between surface hardness and compressive strength should be considered with great caution. In the case of the post-fire assessment, there is commonly a thermal and damage gradient through the depth of the sample. This causes non-uniform concrete strength in the sample and hinders any reliable connection between the member's surface hardness and compressive strength (El-Sayad, 2005).

Despite this key limitation, the use of rebound hammer data for inferring concrete compressive strength post-fire is widespread. When discussing the rebound hammer technique (Stochino *et al.*, 2017) state that it should be used only for damage localization, but they did use the SonReb (SONic + REBound) method (Breysse, 2012b) which employs the results of both rebound hammer (RH) and ultrasonic pulse velocity (UPV) measurements together with the core strength measurements at sample places for calibration to produce the concrete strength throughout the whole structure. (Osman *et al.*, 2017) used an unspecified correlation for obtaining the strength and based on high values for the inferred concrete compressive strength concluded that there was no significant damage to the concrete. (Stawiski, 2006) (Folic *et al.*, 2002) and (Wijaya, 2018) on the other hand use a similar approach but use their assessment of the strength reduction only to determine the damaged areas.

4.1.3 Ultrasonic pulse velocity

Another commonly used NDT in the post-fire assessment is the measurement of ultrasonic pulse velocities (UPV) through concrete. Similarly, as with the surface hardness, there is a strong correlation between the UPV and concrete strength in normal design conditions (Bungey and Millard, 1995). The measurements are made using the sound emitter and sound receiver and can be measured directly and indirectly. Directly, when the receiver and emitter can be placed on the opposite sides of the member (can be used for some columns and beams) and indirectly, when both emitter and receiver are placed on the same surface. Direct measurements provide better results but are often not possible.

Similarly, as for surface hardness measurements, the UPV values were used to explicitly obtain the strength of fire-affected concrete in some post-fire assessment studies (Peker and Pekmezci, 2002; Kose *et al.*, 2006; Aseem *et al.*, 2019; Ali Musmar, 2020). In contrast, in (Cioni *et al.*, 2001; Alonso, 2008; Awoyera *et al.*, 2014; Srinivasan *et al.*, 2014) the technique was used only for the damage localization. The authors of the latter studies stated that with direct measurements it is not possible to take into account the damage gradient and only the averaged damage is obtained. (Stawiski, 2006; Stochino *et al.*, 2017) used UPV measurements for both damage localization and strength assessment.

Using indirect measurements, however, the depth of the fire-induced damaged zone can be obtained (Colombo and Felicetti, 2007). This is done by increasing the distance between the emitter and receiver and assuming that at larger distances the sound waves will travel through the undamaged part of the concrete, with higher pulse propagation velocity, as shown in Figure 5. The top part of the figure presents the time T it takes for the signal to travel from the emitter to the receiver at distance x. The bottom part of the figure shows the path the signal travels through the concrete. Based on this plot it is possible to determine the thickness of the zone where the UPV is lower than 80% of the UPV of undamaged concrete using inverse estimation of the residual velocity profile $V(z)$ (Colombo and Felicetti, 2007). This technique was employed in the post-fire assessment by (Colombo and Felicetti, 2007) and (Dilek, 2007)

It must be mentioned that UPV measurements are highly sensitive to the condition of the surface (it has to be relatively smooth) and the presence of reinforcements and large cracks which have different UPV than concrete (El-Sayad, 2005). In conclusion, similarly to surface hardness measurements, UPV can be used to localize fire-induced damage in the structure with the added benefit that it can also provide an idea of its depth.

4.1.4 Drill resistance

An NDT that is not common in the regular concrete structural assessment, but according to its inventors shows potential for use in the post-fire assessment, is the drill resistance method proposed in (Colombo and Felicetti, 2007). The method in essence measures the energy consumed by an electrical drill at different depths. It is based on the assumption that the more damaged parts of the member will have lower strength and therefore require lower energy to drill through them. The energy needed will increase until the drill reaches undamaged concrete where it will remain constant. Using this technique it is possible to obtain the depth of the damaged layer by finding the position where the energy used stops increasing and becomes constant.

Compared to the two previously mentioned NTDs, drill resistance is not completely non-destructive as it leaves a hole. However, if the drill diameter is small enough, damage can be minimal. The advantage of this method is that, unlike the two methods previously mentioned, it does not require a smooth clean surface, making it more versatile.

4.1.5 Other techniques

The described techniques are not the only techniques that are applied for the post-fire assessment of concrete structures. There are others like impact-echo (Epasto *et al.*, 2010; Krzemień and Hager, 2015), drilling powder analysis (Felicetti, 2016), seismic test using surface waves (Abraham and Dérobert, 2003), load test (Stochino *et al.*, 2017), Windsor probes (Dilek, 2007), concrete neutralization (Ha *et al.*, 2016), Raman Spectroscopy (Kerr *et al.*, 2021), infrared thermal imaging (Zhang *et al.*, 2002). These methods, similar to the more detailed discussed drill resistance method, can provide useful information about the structure's condition but are not often used in the post-fire assessment. For that reason, their advantages and disadvantages are only presented in Table 3.

4.2 Destructive techniques – core samples

The main drawback of NDTs is that they do not provide a direct measurement of concrete strength, but measure some other values that are correlated to it. In contrast, using destructive techniques (DT), it is possible to obtain the strength by destructively taking a sample of the structural element, but as the name suggests, these tests cause additional damage to the structure.

The most commonly used DT is removing a core sample from the member and then testing its compressive strength. This way, precise information about the strength at a certain position in the structure is obtained. This method is useful in the regular concrete assessment and can be used to calibrate other NDTs used (Stochino *et al.*, 2017; Aseem *et al.*, 2019).

Core sample strength as a direct measure of residual strength of the concrete post-fire is the most common way of interpreting the technique, as implemented by (Folic *et al.*, 2002; Peker and Pekmezci, 2002; Kose *et al.*, 2006; Epasto *et al.*, 2010; Jansson *et al.*, 2011; Srinivasan *et al.*, 2014; Ha *et al.*, 2016; Wijaya, 2018; Aseem *et al.*, 2019; Knyziak *et al.*, 2019; Ali Musmar, 2020). However, due to the nature of the fire damage, this approach might often not be justifiable. As previously stated, fire exposure causes a thermal and damage gradient in the concrete element perpendicular to the exposed surface. Therefore, a core sample extracted at the location of the fire damage will not have a uniform strength along its length. Due to the confinement effects at the sample ends during testing, these compression test results are mostly representative of the strength in the middle third of the sample according to (Dilek, 2007). On the other hand, in the case of a thin damage zone (i.e., where the fire duration was limited) and when the top and bottom surface of the core sample are trimmed to create a flat surface, the damaged zone can be almost completely removed (Dilek, 2007). For these reasons, core strength results must be considered with caution. They can underestimate the damage to the structure and in some cases completely miss it.

A further problem with core samples is the occurrence of the cracks perpendicular to their longitudinal axis. These cracks can be consequences of the internal stresses that occur due to differences in thermal expansion inside of the cross-section or the onset of spalling. These cracks can make the whole core unusable for the compression test (Cioni *et al.*, 2001).

Luckily there are a few techniques reported in the literature that approach the core sample in a way that is more adapted for the post-fire assessment. They are based on evaluating the core's properties through its length and, in that way, assess the damage gradient. (Krzemień and Hager, 2015) for example, adopt a very simple approach whereby the core is divided into 4-5 smaller samples which are then tested separately. (Wróblewski and Stawiski, 2020) on the other hand use measurements of UPV at different positions along the core's length in order to determine the depth of the damaged zone. The benefit of this method is that the core is not destroyed and can be used for additional tests. Another approach is to cut the core into thin discs and conduct non-destructive and destructive tests on them to identify properties such as air permeability (Dilek, 2007), water permeability, tensile splitting strength (Dos Santos *et al.*, 2002) and dynamic modulus of elasticity (Park *et al.*, 2014; Park and Yim, 2017).

An additional way to use core samples in the post-fire assessment is to conduct a petrographic analysis on them. As most of the fire-induced damage are cracks at a microscopic level, microscopy can be used to examine in detail all the damage that occurred due to the fire (Ounundi *et al.*, 2019), but also parameters such as crack density (Short *et al.*, 2002)(Georgali and Tsakiridis, 2005) can be measured to obtain the width of the damaged zone. A commonly used technique is measuring the colour change (Short *et al.*, 2001). Extensive details abou this technique, that can be used both as NDT and DT, can be found in (Annerel, 2010). Previously mentioned in Section 2, chemical changes inside of the concrete due to the elevated temperature can be tracked using methods such as spectroscopy (Cioni *et al.*, 2001) or thermo-gravimetric measurements (Alonso, 2008). These or similar methods were implemented in (Cioni *et al.*, 2001; Kose *et al.*, 2006; Colombo and Felicetti, 2007; Alonso, 2008; Epasto *et al.*, 2010; Stochino *et al.*, 2017; Wijaya, 2018; Aseem *et al.*, 2019). These methods, although useful in evaluating fire damage in concrete, are relatively expensive and usually take a relatively longer duration. Also, they are usually qualitative measures of temperature-induced damage in concrete and cannot directly quantify the reduction in mechanical properties of concrete (Kodur and Agrawal, 2021).

4.3 Numerical

Numerical simulation can also be an important tool for damage detection. In the post-fire assessment, numerical simulations can be employed only for structural analysis like in (Peker and Pekmezci, 2002; Ha *et al.*, 2016) or they can be coupled with thermal analysis(Cioni *et al.*, 2001; Molkens *et al.*, 2017; Ali Musmar, 2020; Timilsina *et al.*, 2021). If applied correctly, numerical approaches can provide a wide range of information about both the fire event and the condition of the structure after it. By adding complexity to the numerical analysis a better picture of the post-fire condition of a structure can be obtained in principle. However, with complexity, additional uncertainty is often introduced and therefore results of the simulation must be validated with the measurements obtained at the fire scene. Even though numerical methods are a powerful tool for the post-fire assessment, they can be time-consuming and need an experienced user for reliable results and, for this reason, they are rarely used up to date for that purpose. They however prove to have a very high potential in relation to future developments of the post-fire assessment.

The usual approach for the numerical analysis in post-fire assessments consists of three modelling parts: fire exposure, heat transfer, and structural analysis (Agrawal and Kodur, 2019). In this regard, it is important to highlight that the behaviour during a fire is determinative for the post-fire condition, meaning that for a detailed evaluation the entire fire duration needs to be modelled (Kodur and Agrawal, 2016). Simulations whereby only the post-fire mechanical properties are implemented, will necessarily miss plastic deformations and permanent load redistributions resulting from the performance during the fire.

The ISO834 standardized fire exposure, even though often used in structural fire engineering and some post-fire assessments (Ali Musmar, 2020), is not representative of any real fire scenario (evident also by not including a cooling phase of the fire) and therefore has limited applicability in the post-fire assessment. The fire exposure can be adequately modelled in many ways, from simple parametric curves used by (Kodur and Agrawal, 2021), to more detailed zone models utilized by (Molkens *et al.*, 2017), and even advanced computational fluid dynamics software as demonstrated in (Timilsina *et al.*, 2021).

Once the fire exposure is implemented within the heat transfer analysis to produce the evolution in time of the temperature distribution inside a member, the final part is the structural analysis. Numerous options have been applied in the literature, ranging from simplified capacity assessment using approaches such as the 500 °C isotherm method, which is similar to the method applied by (Kodur and Agrawal, 2021), or the use of a more complex finite element model software as adopted by (Molkens *et al.*, 2017) as part of their effort to corroborate the fire severity by comparing observed residual displacements with simulation results.

4.4 Combination of techniques

The combination of using both NDTs and DTs is a popular approach for the post-fire assessment. Because all techniques have their shortcomings, integrating the results can enhance the assessment (Stochino *et al.*, 2017). However, there are different approaches to combining these techniques. Some authors used different techniques to determine the damage depth. For instance (Dilek, 2007) used the indirect UPV method for damage depth and compared it with the core sample measurements where he measured the reduction of the dynamic modulus of elasticity on 25mm thick disks cut from the core. (Alonso, 2008) on the other hand, used UPV to locate the parts of the structure with fire damage and then used petrographic methods on the core samples to determine its extent. Similarly (Cioni *et al.*, 2001) used the rebound hammer and UPV for damage location, but then used spectroscopy to determine the maximum temperature distribution through the core's length.

Another common way of integrating NDTs and DTs is to use the core sample strength to obtain or calibrate the relationship between the NDT measurements and concrete compressive strength. (Folic *et al.*, 2002) used the rebound hammer measurements, observing that a clear relationship is obtained, but also noting that at some locations with higher cover damage the correlation could not be obtained. (Srinivasan *et al.*, 2014) and (Peker and Pekmezci, 2002) both used UPV and while (Peker and Pekmezci, 2002) presented a clear correlation between UPV and strength (and later used it to map the damage through the structure), (Srinivasan *et al.*, 2014) only noted that there was a good correlation without presenting detailed results. (Stochino *et al.*, 2017) and (Aseem *et al.*, 2019) coupled both the rebound hammer and UPV measurements. (Aseem *et al.*, 2019) used multivariate regression in order to obtain a linear function of both of these measured values using the core strength, while (Stochino *et al.*, 2017) used an exponential function, with both reporting relative errors in the range of 10-20%. It should be emphasized that even though this calibration approach is quite common in concrete assessment, it has its limitation in post-fire applications. Mostly due to the existence of a damage gradient in the material, UPV and core strength tests capture only the average values through the material while the rebound hammer only obtains the properties at the surface level.

No structured approach for reducing uncertainties through the combination of techniques could be identified in the literature. This is a major open problem as in the related field of the assessment of existing structures, this has been identified as one of the key advantages of combining information from different sources in the residual capacity evaluation, see e.g. (Breysse, 2012a). The technical approach to reduce uncertainties through the combination of data from different sources involves Bayesian updating (Vereecken, Eline, 2022). As no studies were identified as part of the literature review which explores such techniques, this is not further elaborated here, but the authors believe such approaches have a high potential in order to reduce uncertainties involved in the post-fire assessment.

4.5 Overview of damage detection techniques

Table 3 summarizes the advantages and disadvantages of the described techniques. Overall, NDTs usually are the best first option. They are fast and cheap and can provide a good estimation of the damage distribution across the structure, in some cases even its depth. However, it must be emphasised that in the post-fire application, they provide only the position of the damage and not its extent. When DTs are considered, they are in general more expensive and sometimes complex. Core sample strength is, however, still the only way to obtain a direct evaluation of the concrete strength. In the post-fire assessment, its effectiveness is hindered due to the presence of the damage gradient and therefore it should preferably be combined with other techniques (Dilek, 2007). Finally, numerical analyses can provide a very detailed picture of the structure's post-fire condition, preferably in combination with other techniques, but are highly complex and require a certain degree of expertise.

Table 3 Benefits and disadvantages of different post-fire assessment techniques

TYPE	INSPECTION TECHNIQUE	PRO	CON
NON-DESTRUCTIVE	Visual	Fast and cheap, fire exposure characterization, damage localization,	User dependent Can be misleading Not quantifiable
	Surface hardness (rebound hammer)	Fast and cheap, damage localization	Not precise, Measures surface hardens not strength, Needs proper calibration
	Ultrasonic Pulse Velocity (UPV)	Fast and cheap, damage localization, can detect damage through the depth,	Needs a flat surface, Measures UPV not strength Needs proper calibration Rebars and crack can interfere
	Drill resistance	Fast and cheap, damage localization, can detect damage through the depth, no need for calibration	Not precise, User dependent Measures drill energy not strength
	Impact-echo	Damage localization, can detect damage through the depth	Difficult analysis Not precise
	Drilling powder analysis	Fast and cheap, damage localization, can detect damage through the depth, no need for calibration	Large scatter in results
	Seismic tests using surface waves	Can detect different layers	Does not provide the strength of the material
	Concrete neutralization	Damage localization	Can be used only on exposed surfaces
	Infrared thermal imaging	Can provide maximum temperature	Slow and expensive, not precise enough
DESTRUCTIVE	Core strength	Provides strength of concrete	Does not provide damage through depth, Unreliable, Slow
	Disk measurements	Can provide damage through the depth	Slow and expensive Does not provide strength
	Microscopy	Can provide damage through the depth	Slow and expensive Does not provide strength
	Thermo-gravimetric analysis	Can provide damage through the depth	Slow and expensive Does not provide strength
	Colorimetry	Can provide damage through the depth	Slow and expensive Does not provide strength

NUMERICAL		Can provide detailed information on the damage, reduced capacity and overall structure's condition	Sensitive to inputs Slow and expensive

There is a large number of techniques used in the post-fire assessment and not all of them are discussed in detail here, However, Table 4 presents a short recapitulation of the main characteristics of most of the assessment techniques found in literature accompanied by the information they provide. The first characteristic describes whether the results are objective or need expert judgement. Next, it is assessed whether the technique needs some kind of calibration or validation for each case and it is assessed whether the technique is fast and cheap to be implemented. Furthermore, Table 5 summarizes the techniques used in different case studies found in the literature.

Table 4 Overview of post-fire assessment techniques' characteristics and information the techniques provide

TYPE	NAME	Objective	Calibration / validation	Fast / cheap	Fire severity characterizatio	Damage localization	Damage depth	Temperature distribution	Residual strength
NON-DESTRUCTIVE	Visual	-	-	+	+	+	-	-	-
	Surface hardness (rebound hammer)	+	+	+	-	+	-	-	-
	Ultrasonic Pulse Velocity	+	+	+	-	+	+/-	-	-
	Drill resistance	+	-	+	-	+	+	-	-
	Impact-echo	+	+	-	-	+	+	-	-
	Drilling powder analysis	+	-	+	-	+	+	+/-	-
	Seismic test	+	+	-	-	+	+/-	-	-
	Concrete neutralization	+	-	+	-	+	+/-	+/-	-

	Infrared thermal imaging	+	+	-	-	+	-	+	-
DESTRUCTIVE	Core strength	+	-	-	-	+/-	-	-	+/-
	Disk measurements	+	+	-	-	+/-	+	+/-	+/-
	Microscopy	-	-	-	-	+/-	+	+/-	-
	Thero-gravimetric	+	-	-	-	+/-	+	+	-
	Colouromtery	-	-	-	-	+/-	+	+	-
NUM.	Numerical	+	+/-	-	+/-	+	+	+	+

5 Assessment of the residual load-bearing capacity

The explicit assessment of the residual post-fire capacity of concrete members is surprisingly rare in the literature, even though most authors agree it is a necessary part of the post-fire assessment. Multiple experimental studies focusing on the post-fire behaviour of concrete members can be found in literature, e.g. (Nassif, 2006; Chen *et al.*, 2009; Agrawal and Kodur, 2019). These studies apply the fire exposure in a controlled setting and focus on improving the understanding regarding the mechanical post-fire behaviour of concrete structures. The current review, however, focuses on the assessment itself, and thus these experimental studies are excluded (Cioni *et al.*, 2001; Abraham and Dérobert, 2003; Colombo and Felicetti, 2007; Epasto *et al.*, 2010; Wróblewski and Stawiski, 2020) were focused on demonstrating the effectiveness of the novel techniques they developed and presented, with damage detection and the assessment of the load-bearing capacity suggested as a next step.

On the other hand, studies like in (Alonso, 2008; Jansson *et al.*, 2011; Aseem *et al.*, 2019; Timilsina *et al.*, 2021) report case studies concerned with the post-fire assessment, not introducing new techniques, but also not reporting on the capacity assessment, implying that their actual goal was damage detection.

Where residual capacity is assessed, the approaches differ widely. (Ha *et al.*, 2016) calculated the residual capacity of an RC beam using FEM and by modelling the damage as a layer in the cross-section with reduced mechanical properties. They opted to reduce 40% of the compressive strength of a 50 mm thick layer of concrete, which they considered conservative based on the results of the NDT and DTs. As the numerical analysis showed that even this reduced cross-section had a higher capacity than the design loads, they considered the structure safe. No thermo-mechanical analysis was conducted in this study. Therefore, this FEM evaluation can be considered very simplified.

(Kodur and Agrawal, 2021) also used a simplified method to assess the capacity of an RC beam and explicitly took into account the estimated fire exposure. They estimated the maximum temperature which the compressed concrete and tensioned reinforcement experienced using a correlation linking them to the maximum temperature in the compartment. The estimated maximum temperatures were used to determine the reduced mechanical properties which were next used as input in a simplified cross-sectional approach to calculate the residual capacity of the beam.

More advanced numerical models were adopted in (Molkens *et al.*, 2017), (Ali Musmar, 2020), (Peker and Pekmezci, 2002) and (Cioni *et al.*, 2001). (Molkens *et al.*, 2017) used software SAFIR (Franssen and Gernay, 2017) to conduct an advanced thermo-mechanical model which included both the thermal and non-linear finite element mechanical analysis. They validated the model results using the measured residual deformations of the slab. Furthermore, they took into account the uncertainties on both the fire exposure and the mechanical properties in the final capacity assessment. (Ali Musmar, 2020) on the other hand, used a similarly complex numerical model (ANSYS software), but instead of the natural fire exposure, the standardized fire exposure was used. This, coupled with the fact that no result validation was conducted, makes the residual capacity estimation much more difficult to interpret.

A potentially interesting demonstration of combining advanced numerical methods with information from NDT and DT has been presented by (Peker and Pekmezci, 2002). They conducted a 3D FEM simulation, where they used reduced mechanical properties of different parts of the structure based on the NDTs and DTs. Unfortunately, not many details on both the model and its results were provided. Similarly, but with a more elaborate description of the results, (Cioni *et al.*, 2001) presented a numerical analysis, where both the heat transfer and mechanical analysis are conducted. Validation of the heat transfer is conducted using the results of the recorded thermo-chemical reactions, i.e. the maximum temperatures through depth that the member experienced. The numerical analysis provided maximum stresses in the cross-section that can later be used for the safety evaluation.

From the above succinct discussion of literature cases, it is evident that the determination of the residual capacity varies greatly in different studies. Often, no explicit evaluation of the residual capacity is made. This is notably the case in studies where the focus was on the damage detection and residual strength determination. In such situations, the capacity evaluation can be considered implicit and based on expert judgement. However, in most studies where the residual capacity was explicitly evaluated, the evaluation was done based on the information about the fire exposure and temperature distribution inside of the material. A limited number of studies used advanced numerical methods together with a very simplified consideration of the fire damage, such as natural fire exposure. In such situations, the additional precision obtained through the advanced method is effectively lost due to the crudeness in the fire exposure modelling. As in general structural fire safety engineering, it is thus recommendable to pursue a “consistency of crudeness” (Buchanan, 2008). A similar trend is noticeable in the rehabilitation recommendations, where authors of these studies usually base their recommendations on engineering judgement. This is presented in more detail in the following section.

6 Evaluation and intervention strategy

The assessment result should, as highlighted in the review of the goal and post-fire assessment framework in Section 2, answer the question if the structure is safe or should be repaired (or demolished if repair is too costly). Similarly to almost every aspect of the post-fire assessment, the way this question is addressed varies. The recommendation is most commonly based on engineering judgement, e.g., (Folic *et al.*, 2002; Stawiski, 2006; Dilek, 2007; Gosain *et al.*, 2008; Awoyera *et al.*, 2014; Srinivasan *et al.*, 2014; Stochino *et al.*, 2017; Wijaya, 2018; Knyziak *et al.*, 2019). In these cases, the decision of whether and how the structure will be repaired is based on the detected damage and the authors' judgment. In (Folic *et al.*, 2002) for example, a combination of the rebound hammer and core sample strength tests was used. The results showed that there was a clear distinction in the results of the fire-exposed floors and those unaffected by the fire, but there was no precise damage quantification except the average reduced compressive strength per floor. They suggested repair methods such as “removal of the damaged concrete cover up to the sound concrete” even though no assessment of the damage depth was made.

Similarly, (Stochino *et al.*, 2017) presented an integrated method for the post-fire assessment of concrete structures. They adopted a wide range of methods and by understanding the capability of each technique, the authors were able to obtain reliable recognition of the thermal zoning of fire-exposed concrete. However, no proper rehabilitation recommendations were given except concluding that “refurbishment is needed”. Nevertheless, Stochino et al. mention that the next step should be to use their results for numerical modelling to obtain an even better picture of the structure's condition.

As a final example of a recommendation ultimately based on expert judgement, in (Dilek, 2007) it was concluded that the damage was localized in the surface layer of 25 mm, based on a combination of indirect UPV method and dynamic modulus of elasticity and air permeability tests on 25mm discs cut from concrete cores. Taking into account compression tests on additional core samples which did not show any significant strength change through the depth, the authors concluded that the removal and replacement of the damaged concrete zone would be the best option.

On the other hand, when authors explicitly evaluated the residual capacities of the fire-exposed members, rehabilitation recommendations are rarely based on the engineering judgement, but on some form of safety assessment. (Ha *et al.*, 2016) and (Kodur and Agrawal, 2021) compared the calculated residual capacity with the design loads and in both studies, the residual capacity was significantly higher which led the authors to conclude that the structure is safe for further use. While such safety assessment is indicative of some strength margin within the structure, it does not clarify whether the structure achieves the safety level required by design codes. After all, design codes define design requirements through a specification of maximum acceptable failure probabilities (i.e., minimum reliability indices) (Vrouwenvelder, 2002).

(Molkens *et al.*, 2017) performed a safety evaluation in accordance with the reliability requirements for design. Instead of using a single evaluation of the residual capacity, a full-probabilistic calculation was conducted, using the post-fire assessment approach described in (Van Coile *et al.*, 2014b) taking into account uncertainties of multiple influential parameters. This allowed determining a maximum characteristic value for the live load that would provide an adequate safety level (here, a reliability index of 3.8, in accordance with the normal design requirement of EN 1990. Their work highlighted the importance of taking into account uncertainties of the data as part of the post-fire assessment.

Considering the available literature, there seems to be a clear distinction between two approaches within post-fire assessment calculations. The first one is focused on damage detection, in the sense of determining the parts of the structure where the mechanical properties are reduced due to the fire effect, and recommending their replacement as an adequate method for rehabilitation. The second more elaborate approach is to determine the fire exposure characteristics and base the recommendations for rehabilitation on a comparison of the loads on the structure with an assessed residual capacity (possibly, including an assessment of uncertainties and residual safety level). This approach thus focuses on the thermal distribution inside of the material. Based on those temperatures and known relationships with mechanical properties, the residual capacity of the members is evaluated. The safety level and future actions are then assessed based on the loads on the structure. Considering the post-fire assessment's stated goal of evaluating whether the structure is safe for continued use, only the latter approach achieves its ultimate objective. However, even when this approach is used, uncertainties are usually not considered. This can lead to a too high confidence in the assessment results which can have a significant effect on the evaluation of the structure's safety level. As mentioned, design codes define design requirements through a direct or indirect specification of maximum acceptable failure probabilities and ignoring uncertainties hinders this evaluation. An overview of the methods used in the case studies is presented in Table 6.

7 Conclusions

A wide range of post-fire assessment related investigations of concrete structures has been found in literature. Overall, there seems to be no common agreement on the goal of the assessment, on how it should be conducted and what techniques should be used. Furthermore, given the wide range of situations where a post-fire assessment is needed and the wide range of techniques available, it is probably not possible to create a robust step-wise approach applicable for all situations at this time. However, there is a need and possibility for a framework and universal guidelines which would define the purpose, key components, and targets of a post-fire assessment.

Overall, two distinctive approaches can be noticed. The first one is essentially focused on damage detection. Where multiple techniques are used to locate the parts of the structure where there is significant fire damage and subsequently what is its extent. This is done with the purpose to determine which parts should be removed and replaced in order to make the structure safe for future use.

The second approach is mostly focused on evaluating the residual load-bearing capacity of the structure. Usually, the first step is to characterize the fire exposure in order to reconstruct the temperature distribution the member experienced. Based on this, the residual capacity is estimated, which is then used to decide the best option for rehabilitation.

Available assessment techniques can be grouped into two categories: non-destructive (NDT) and destructive (DT). NDTs are quite often used as they are usually fast and easy to carry out and most importantly they have a minimal effect on the structure. Visual inspection is the most basic and most used method. NDTs can be a powerful tool for localizing the parts of the structure that experienced significant damage and in some cases even determining its extent. However, they are commonly used to determine the residual strength of damaged concrete, with results which can possibly be misleading due to the existence of a damage gradient in the specimens. DTs are more invasive techniques, but can usually provide much more information about the damage the structure encountered due to the fire. Even more often than the NDTs, they are used to determine the residual strength of the concrete, but similarly, the results can be unreliable due to the damage gradient.

Further to the aforementioned empirical techniques, numerical methods are available. That enable to perform damage identification and provide a precise evaluation of a structure's residual capacity. However, fire events and the associated structural response are complex phenomena, meaning numerical methods have to be used with great care. Using other techniques alongside numerical methods for validation can improve confidence in the results. Furthermore, additional uncertainty from the model itself and the parameters used for it must be considered. Hence, numerical methods often require significant time and expertise to yield reliable results.

Even though post-fire assessments deal with highly complex events characterized by a large number of uncertainties, these uncertainties are rarely explicitly considered. The usual practice of ignoring uncertainties produces overconfidence in the assessment results. Probably as a consequence, the safety level of the structure is seldom evaluated. Most of the time, the rehabilitation plan, (i.e., whether and to what extent the structure should be repaired) is based on engineering judgement without any explicit safety assessment.

Considering the above, additional research in the post-fire assessment of concrete structures is recommended to focus firstly on the development of an integrated approach combining multiple techniques. This will produce the best results as it will overcome the individual disadvantages of techniques and generally reduce uncertainties in the assessment. Furthermore, these uncertainties in the assessment should be considered explicitly to avoid false confidence in the assessment results. Finally, clear safety targets and ways to achieve them are needed. This will alleviate the need to rely on engineering judgement and produce a more reliable assessment end result.

Table 5 Case studies and used techniques

	NON-DESTRUCTIVE				DESTRUCTIVE			NUMERICAL
Reference	**Visual**	**Rebound Hammer**	**UPV**	**Other**	**Core strength**	**Petrography**	**Other**	**Numerical**
(Stochino *et al.*, 2017)	+	+	+	Color spay	+	+	Load test	
(Colombo and Felicetti, 2007)	+	+	+	Drill resistance		+		
(Epasto *et al.*, 2010)	+			Impact echo	+	+		
(Abraham and Dérobert, 2003)				Seismic tests				
(Dilek, 2007)	+		+	Windsor	+		Disk measurements	
(Ha *et al.*, 2016)	+			Neutralization	+		Rebar sample	+
(Wróblewski and Stawiski, 2020)					+		UPV per length	
(Cioni *et al.*, 2001)	+	+	+		+	+	Spectroscopy	+
(Alonso, 2008)	+		+		+	+	Thermo-gravimetric	
(Osman *et al.*, 2017)	+	+						
(Kose *et al.*, 2006)	+	+			+	+		
(Srinivasan *et al.*, 2014)	+	+	+		+			
(Awoyera *et al.*, 2014)	+	+	+					
(Stawiski, 2006)		+	+					
(Folic *et al.*, 2002)	+	+			+	+		
(Knyziak *et al.*, 2019)	+	+	+		+			
(Gosain *et al.*, 2008)	+	+	+		+		Steel samples	
(Jansson *et al.*, 2011)	+				+			
(Wijaya, 2018)	+	+			+	+	Rebar test	
(Aseem *et al.*, 2019)	+	+	+		+	+		
(Timilsina *et al.*, 2021)	+			Deformations				+
(Molkens *et al.*, 2017)	+			Deformations				+
(Ali Musmar, 2020)	+	+	+		+			+
(Peker and Pekmezci, 2002)	+		+		+			+

Table 6 Recap of the methods used in the case studies

Reference	**Damage detection and identification**	**Residual performance evaluation**	**Rehabilitation recommendations**
(Stochino *et al.*, 2017)	+		+
(Colombo and Felicetti, 2007)	+		
(Epasto *et al.*, 2010)	+		
(Abraham and Dérobert, 2003)	+		
(Dilek, 2007)	+		+
(Ha *et al.*, 2016)	+	+	+
(Wróblewski and Stawiski, 2020)	+		
(Cioni *et al.*, 2001)	+	+	
(Alonso, 2008)	+		
(Osman *et al.*, 2017)	+	+	+
(Kose *et al.*, 2006)	+		
(Srinivasan *et al.*, 2014)	+		+
(Awoyera *et al.*, 2014)	+		+
(Stawiski, 2006)	+		+
(Folic *et al.*, 2002)	+		+
(Knyziak *et al.*, 2019)	+		+
(Gosain *et al.*, 2008)	+		+
(Jansson *et al.*, 2011)	+		+
(Wijaya, 2018)	+		+
(Aseem *et al.*, 2019)	+		
(Timilsina *et al.*, 2021)	+		
(Molkens *et al.*, 2017)	+	+	+
(Ali Musmar, 2020)	+	+	+
(Kodur and Agrawal, 2021)	+	+	+
(Peker and Pekmezci, 2002)	+	+	+

Acknowledgements

The authors wish to thank the Research Foundation of Flanders (FWO) for the financial support on the research project (Grant number 3G010220) "Vibration-based post-fire assessment of concrete structures using Bayesian updating techniques".

References

Abraham, O. & Dérobert, X. 2003. Non-destructive testing of fired tunnel walls: The Mont-Blanc Tunnel case study, *NDT and E International*, 36(6), pp. 411–418. doi: 10.1016/S0963-8695(03)00034-3.

Agrawal, A. & Kodur, V. K. R. R. 2019. A Novel Experimental Approach for Evaluating Residual Capacity of Fire Damaged Concrete Members, *Fire Technology*, 56(2), pp. 715–735. doi: 10.1007/s10694-019-00900-1.

Ali Musmar, M. 2020. A case study on fire damage assessment of a two-story building with precast pretensioned hollow core slabs, *Journal of King Saud University - Engineering Sciences*, pp. 501–509. doi: 10.1016/j.jksues.2019.09.003.

Alonso, C. 2008. Assessment of post-fire reinforced concrete structures. Determination of depth of temperature penetration and associated damage, in *Concrete repair, rehabilitation and retrofitting II*. CRC Press, pp. 217–218.

Annerel, E. 2010. *Assessment of the residual strength of concrete members after fire exposure, Doctoral dissertation*. Ghent University, Department of Structural engineering.

Aseem, A. *et al.* 2019. Structural health assessment of fire damaged building using non-destructive testing and micro-graphical forensic analysis: A case study, *Case Studies in Construction Materials*, 11, p. e00258. doi: 10.1016/j.cscm.2019.e00258.

Awoyera, P. *et al.* 2014. Forensic Investigation of Fire-affected Reinforced Concrete Buildings, *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*, 11, pp. 17–23. doi: 10.9790/1684-11441723.

Beitel, J. & Iwankiw, N. 2005. Historical Survey of Multi-Story Building Collapses Due to Fire, *Fire Protection Engineering*, 27.

Breysse, D. 2012a. *Non-destructive assessment of concrete structures: Reliability and limits of single and combined techniques: State-of-the-art report of the RILEM technical committee 207-INR*. Springer Science & Business Media. doi: 10.1016/j.conbuildmat.2011.12.103.

Breysse, D. 2012b. Nondestructive evaluation of concrete strength: An historical review and a new perspective by combining NDT methods, *Construction and Building Materials*, 33, pp. 139–163. doi: 10.1016/j.conbuildmat.2011.12.103.

Buchanan, A. 2008. The challenges of predicting structural performance in fires, *Fire Safety Science*, 9, pp. 79–90.

Bungey, J. H. & Millard, S. G. 1995. *Testing of Concrete in Structures*, *Testing of Concrete in Structures*. Crc Press. doi: 10.4324/9780203487839.

CEN 2004. EN 1992-1-2:2004: Eurocode 2: Design of concrete structures - Part 1-2: General rules. Structural fire design. European Standard.

CEN 2005. EN 1994-1-2:2005 Eurocode 4: Design of composite steel and concrete structures - Part 1-2 General rules - Structural fire design, European Standard. European Standard.

Chen, Y. H. *et al.* 2009. Experimental research on post-fire behaviour of reinforced concrete columns, *Fire Safety Journal*. doi: 10.1016/j.firesaf.2009.02.004.

Chew, M. Y. L. 1993. The assessment of fire damaged concrete, *Building and Environment*, 28(1), pp. 97–102. doi: 10.1016/0360-1323(93)90010-Z.

CIB W14 Report 1990. Repairability of Fire Damaged Structures, *Fire Safety Journal*, 16, pp. 251–336.

Cioni, P., Croce, P. & Salvatore, W. 2001. Assessing fire damage to r.c. elements, *Fire Safety Journal*, 36(2), pp. 181–199. doi: 10.1016/S0379-7112(00)00050-3.

Colombo, M. & Felicetti, R. 2007. New NDT techniques for the assessment of fire-damaged concrete structures, *Fire Safety Journal*, 42(6–7), pp. 461–472. doi: 10.1016/j.firesaf.2006.09.002.

Dilek, U. 2007. Assessment of Fire Damage to a Reinforced Concrete Structure during Construction, *Journal of Performance of Constructed Facilities*, 21(4), pp. 257–263. doi: 10.1061/(asce)0887-3828(2007)21:4(257).

El-Sayad, H. I. 2005. Limitations in Using Non Destructive Tests for Assessment of Concrete Subject To Elevated Temperature, *Journal of the Faculty of Engineering-Mattaria*, 99, pp. C42–C60.

Epasto, G., Proverbio, E. & Venturi, V. 2010. Evaluation of fire-damaged concrete using impact-echo method, *Materials and Structures/Materiaux et Constructions*, 43(1–2), pp. 235–245. doi: 10.1617/s11527-009-9484-0.

Felicetti, R. 2016. Assessment of fire damage in concrete structures : new inspection tools and combined interpretation of results, *8th International Conference on Structures in Fire Shanghai, China*, (June 2014), pp. 1111–1120. Available at: https://re.public.polimi.it/handle/11311/977098 (Accessed: 15 November 2022).

fib 2007. Fire design of concrete structures-materials, structures and modeling, *FIB Bulletin 38*. Fédération International du Béton

Folic, R., Radonjanin, V. & Malesev, M. 2002. The assessment of the structure of Novi Sad Open University damaged in a fire, *Construction and Building Materials*, 16(7), pp. 427–440. doi: 10.1016/S0950-0618(02)00045-4.

Franssen, J.-M. & Gernay, T. 2017. Modeling structures in fire with SAFIR®: theoretical background and capabilities, *Journal of Structural Fire Engineering*, 8(3), pp. 300–323. doi: 10.1108/JSFE-07-2016-0010.

Georgali, B. & Tsakiridis, P. E. 2005. Microstructure of fire-damaged concrete. A case study, *Cement and Concrete Composites*, 27(2), pp. 255–259. doi: 10.1016/j.cemconcomp.2004.02.022.

Gosain, N. K., Drexler, R. F. & Choudhuri, D. 2008. Evaluation and Repair of Fire-Damaged Buildings, *Structural Engineering Magazine*, 30(September), pp. 1–11. Available at: http://www.structuremag.org/article.aspx?articleID=749.

Ha, T. *et al.* 2016. A case study on the rehabilitation of a fire-damaged structure, *Applied Sciences*, 6(5). doi: 10.3390/app6050126.

Jansson, R. *et al.* 2011. Fire in storehouse 6 in the free port of Stockholm, in *2nd International RILEM Workshop on Concrete Spalling due to Fire Exposure*, pp. 205–210.

Kakae, N. *et al.* 2017. Physical and thermal properties of concrete subjected to high temperature, *Journal of Advanced Concrete Technology*, 15(6), pp. 190–212. doi: 10.3151/jact.15.190.

Kerr, T., Vetter, M. & Gonzalez-Rodriguez, J. 2021. Evaluating residual compressive strength of post-fire concrete using Raman Spectroscopy, *Forensic Science International*, 325. doi: 10.1016/j.forsciint.2021.110874.

Khiyon, M. I. *et al.* 2017. Preliminary assessment of fire damaged reinforced concrete structure and steel truss, *Malaysian Journal of Civil Engineering*, 29(2), pp. 195–204. doi: 10.11113/mjce.v29.143.

Khoury, G. A. 1996. Performance of heated concrete - mechanical properties, *Performance of Heated Concrete - Mechanical Properties*.

Khoury, G. A. 2000. Effect of fire on concrete and concrete structures, *Progress in Structural Engineering and Materials*, 2(4), pp. 429–447. doi: https://doi.org/10.1002/pse.51.

Knyziak, P., Kowalski, R. & Krentowski, J. R. 2019. Fire damage of RC slab structure of a shopping center, *Engineering Failure Analysis*, 97, pp. 53–60. doi: 10.1016/j.engfailanal.2018.12.002.

Kodur, V. 2014. Properties of concrete at elevated temperatures, *ISRN Civil Engineering*, 2014. doi: 10.1155/2014/468510.

Kodur, V. K. R. & Agrawal, A. 2016. An approach for evaluating residual capacity of reinforced concrete beams exposed to fire, *Engineering Structures*, 110, pp. 293–306. doi: 10.1016/j.engstruct.2015.11.047.

Kodur, V. K. R. & Agrawal, A. 2017. Effect of temperature induced bond degradation on fire response of reinforced concrete beams, *Engineering Structures*. doi: 10.1016/j.engstruct.2017.03.022.

Kodur, V. K. R. & Agrawal, A. 2021. Estimating Postfire Residual Capacity of Heavily Damaged Concrete Members, *Journal of Performance of Constructed Facilities*, 35(2), p. 04020151. doi: 10.1061/(asce)cf.1943-5509.0001561.

Kose, M. M., Temiz, H. & Binici, H. 2006. Effects of fire on precast members: A case study, *Engineering Failure Analysis*, 13(8), pp. 1191–1201. doi: 10.1016/j.engfailanal.2005.12.003.

Krzemień, K. & Hager, I. 2015. Post-fire assessment of mechanical properties of concrete with the use of the impact-echo method, *Construction and Building Materials*, pp. 155–163. doi: 10.1016/j.conbuildmat.2015.08.007.

Li, Y. H. & Franssen, J. M. 2011. Test results and model for the residual compressive strength of concrete after a fire, *Journal of Structural Fire Engineering*. doi: 10.1260/2040-2317.2.1.29.

Lie, T. T. & Kodur, V. K. R. 1996. Thermal and mechanical properties of steel-fibre-reinforced concrete at elevated temperatures, *Canadian Journal of Civil Engineering*, 23(2), pp. 511–517. doi: 10.1139/l96-055.

Molkens, T., Van Coile, R. & Gernay, T. 2017. Assessment of damage and residual load bearing capacity of a concrete slab after fire: Applied reliability-based methodology, *Engineering Structures*, 150, pp. 969–985. doi: 10.1016/j.engstruct.2017.07.078.

Nassif, A. 2006. Postfire full stress-strain response of fire-damaged concrete, *Fire and Materials*, 30(5), pp. 323–332. doi: 10.1002/fam.911.

Neves, I. C., Rodrigues, J. P. C. & Loureiro, A. de P. 1996. Mechanical Properties of Reinforcing and Prestressing Steels after Heating, *Journal of Materials in Civil Engineering*, 8(4). doi: 10.1061/(asce)0899-1561(1996)8:4(189).

Osman, M. H. *et al.* 2017. A case study on the structural assessment of fire damaged building, in *IOP Conference Series: Materials Science and Engineering*. doi: 10.1088/1757-899X/271/1/012100.

Ounundi, L. O., Oumarou, M. Ben & Alkali, A. M. 2019. Effects of Fire on the Strength of Reinforced Concrete Structural Members, *American Journal of Civil Engineering and Architecture*, 7(1), pp. 1–12. doi: 10.12691/ajcea-7-1-1.

Park, G. K. & Yim, H. J. 2017. Evaluation of Fire-Damaged Concrete: An Experimental Analysis based on Destructive and Nondestructive Methods, *International Journal of Concrete Structures and Materials*, 11(3), pp. 447–457. doi: 10.1007/s40069-017-0211-x.

Park, S., Jae, H. & Kwak, H. 2014. Nonlinear resonance vibration method to estimate the damage level on heat-exposed concrete, *Fire Safety Journal*, 69, pp. 36–42. doi: 10.1016/j.firesaf.2014.07.003.

Peker, K. & Pekmezci, B. 2002. Damage Analysis For A 210 Minute Fire Exposed Industrial Structure, *Structural engineering international*, 13(4), pp. 245–248.

Qureshi, R. *et al.* 2020. Probabilistic models for temperature dependent strength of steel and concrete, *Journal of Structural Engineering*, 146(6), p. 04020102. doi: 10.1061/(asce)st.1943-

541x.0002621.

Dos Santos, J. R., Branco, F. A. & De Brito, J. 2002. Assessment of concrete structures subjected to fire - The FBTest, *Magazine of Concrete Research*, 54(3). doi: 10.1680/macr.2002.54.3.203.

Shahraki, M. *et al.* 2022. Residual compressive strength of concrete after exposure to high temperatures: A review and probabilistic models, *Fire Safety Journal*, p. 103698.

Short, N. R., Purkiss, J. A. & Guise, S. E. 2001. Assessment of fire damaged concrete using colour image analysis, *Construction and Building Materials*, 15(1), pp. 9–15. doi: 10.1016/S0950-0618(00)00065-9.

Short, N. R., Purkiss, J. A. & Guise, S. E. 2002. Assessment of fire-damaged concrete using crack density measurements, *Structural Concrete*, 3(3), pp. 137–143. doi: 10.1680/stco.3.3.137.38957.

Srinivasan, P. *et al.* 2014. Evaluation of fire-damaged concrete structures with a case study, in *National Conference on Fire Research and Engineering*. Roorkee, India, p. 029.

Stawiski, B. 2006. Attempt to estimate fire damage to concrete building structure, *Archives of Civil and Mechanical Engineering*, 6(4), pp. 23–29. doi: 10.1016/S1644-9665(12)60273-8.

Stochino, F. *et al.* 2017. Integrated approach for post-fire reinforced concrete structures assessment, *Periodica Polytechnica Civil Engineering*, 61(4), pp. 677–699. doi: 10.3311/PPci.9830.

Taerwe, L. *et al.* 2008. Fire design of concrete structures - structural behaviour and assessment, *fib bulletin*, 46, pp. 3–8.

Timilsina, S., Yazdani, N. & Beneberu, E. 2021. Post-fire analysis and numerical modeling of a fire-damaged concrete bridge, *Engineering Structures*, 244. doi:

10.1016/j.engstruct.2021.112764.

Van Coile, R., Caspeele, R. & Taerwe, L. 2014a. Reliability-based evaluation of the inherent safety presumptions in common fire safety design, *Engineering Structures*, 77, pp. 181–192. doi: 10.1016/j.engstruct.2014.06.007.

Van Coile, R., Caspeele, R. & Taerwe, L. 2014b. Towards a reliability-based post-fire assessment method for concrete slabs incorporating information from inspection, *Structural Concrete*, 15(3), pp. 395–407. doi: 10.1002/suco.201300084.

Vereecken, Eline 2022. *Applied Bayesian pre-posterior and life-cycle cost analysis for determining and optimizing the value of structural health monitoring for concrete structures*. Ghent University. Faculty of Engineering and Architecture.

Vrouwenvelder, A. C. W. M. 2002. Developments towards full probabilistic design codes, *Structural Safety*, 24(2–4), pp. 417–432. doi: 10.1016/S0167-4730(02)00035-8.

Wijaya, G. 2018. Comprehensive condition assessment program on the fire damaged structure - a project case in Singapore, *MATEC Web of Conferences*, 195, p. 2034. doi: 10.1051/matecconf/201819502034.

Wróblewski, R. & Stawiski, B. 2020. Ultrasonic assessment of the concrete residual strength after a real fire exposure, *Buildings*, 10(9), pp. 1–13. doi: 10.3390/buildings10090154.

Zhang, X. *et al.* 2002. Assessment of Fire Damage of Concrete By Using Infrared Thermal Imaging Method, in *Challenges of Concrete Construction: Volume 6, Concrete for Extreme Conditions*, pp. 595–604. doi: 10.1680/cfec.31784.0058.

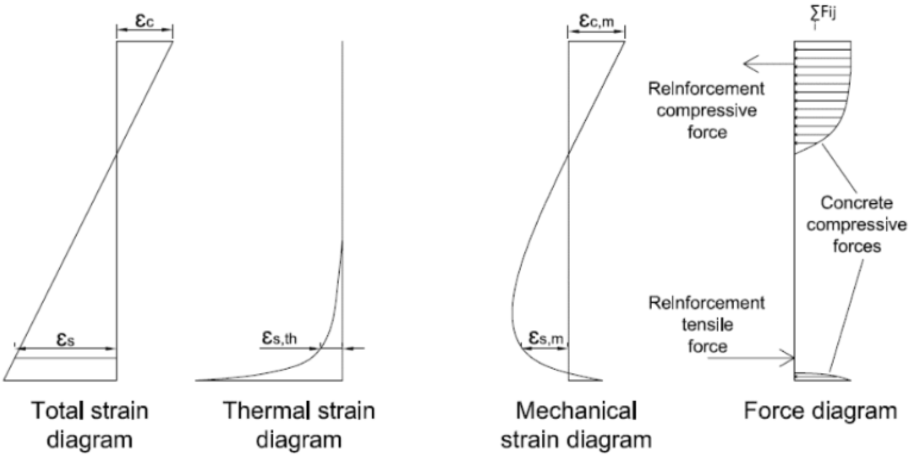

Figure 1 Stress distribution of the reinforced concrete slab exposed to the fire from the bottom side ε_c *represents the strain in the top concrete fiber and* ε_s *in the bottom reinforcement* (Van Coile *et al.*, 2014a)

Figure 2 Spalling example

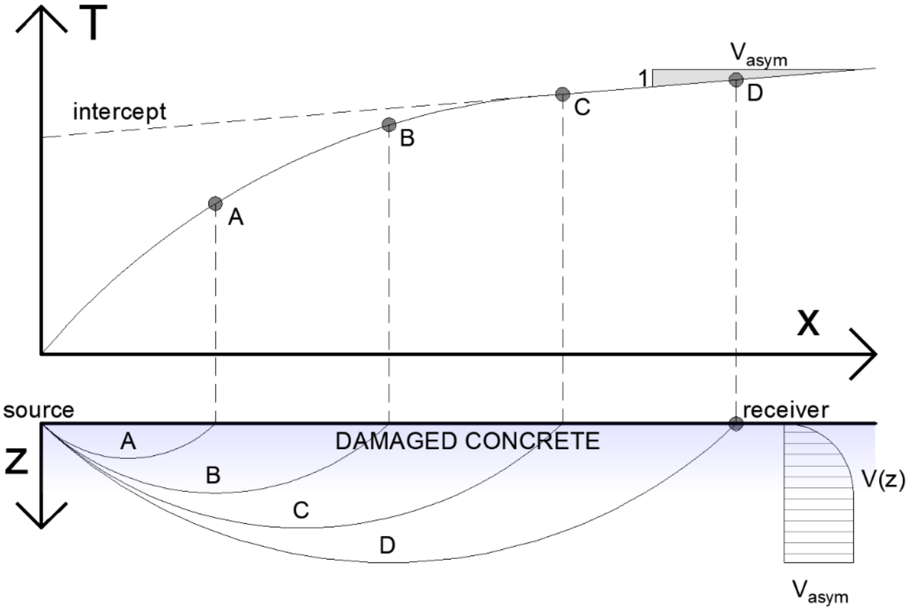

Figure 3 Indirect method of measuring UPV in order to obtain the damaged layer depth using inverse estimation of the residual velocity profile V(z) (Colombo and Felicetti, 2007)