Concrete Damage and Spalling Monitoring in Fire Tests via Ultrasonic Pulse-Echo and Ground-Penetrating Radar

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Abstract
Spalling in concrete during fire still needs to be fully understood, since the complex interaction of different aspects, such as pore pressure, thermal and load-induced stresses, as well as material physico-mechanical damage and heating rate, makes difficult the comprehension of the mechanisms behind this phenomenon. Within this context, monitoring the progress of spalling and moisture migration during heating is a challenging task, being most of the available techniques hardly suitable for the implementation in the test furnace. Among the Real-Time survey techniques, promising results were obtained from Ultrasonic Pulse-Echo (UPE) and Ground-Penetrating Radar (GPR), both based on the evaluation of the echo delay and attenuation of the waves reflected by the specimen side exposed to fire.

UPE and GPR were implemented in the case of fire tests performed on concrete slabs subjected to heating at the bottom face, and the results are discussed in the present paper.

Keywords: Concrete, ground-penetrating radar, high temperature, spalling monitoring, ultrasonic pulse-echo.

1. Introduction
Concrete is often addressed as a material able to guarantee good structural performances in fire, thanks to its incombustibility and low thermal diffusivity. Anyway special attention should be paid to mix design and structural detailing in order to enhance the fire resistance of the structure, by reducing the detrimental effects brought in by material mechanical decay due to high temperature and by thermal-induced loads. Furthermore, spalling can strongly affect the mechanical response of R/C members during fire.

Spalling in concrete members subjected to heating is the more or less violent expulsion of chunks from the exposed face and can leading to the dramatic decrease of the fire resistance due to the reduction of the section geometry and the possible direct exposure of the reinforcing bars to the flames.

Spalling is made particularly tricky by the mutual interaction of different influencing factors (heating rate, concrete thermo-physical properties, initial moisture content and saturation level) and parameters (pore pressure and stress) [1-4]. It is generally agreed that spalling is the outcome of two main actors: (a) stress induced by thermal gradients and external loads and (b) pore pressure rise caused by water saturation and vaporization.

The low thermal diffusivity of concrete, in fact, leads to significant thermal gradients during heating, which yield compressive and tensile stress (parallel to the heated face) in the hot layers and in the inner core respectively. The former can trigger cracking parallel to the isothermal surfaces with the subsequent decrease of the local mechanical stability. Kinematic incompatibility between aggregate and cement paste, release of absorbed and chemically bound water and cement dehydration can also favour cracking [4].

Fluid pressure in the pores, on the other hand, is caused by the dilation of dry air and liquid water (if saturation occurs) and to the vaporization process. Pressure gradients cause moisture migration towards both the hot face and the inner core. In this last case, the water saturation level can increase due to flow of liquid water and to the possible condensation of vapour [2], even up to the formation of a quasi-saturated layer. In dense materials, such as High-Performance Concrete (HPC), saturation can be attained (so-called moisture clog) and the
reduced permeability can dramatically enhance pressure build-up with values up to 5 MPa [1]. This is the reason why spalling is a concern in HPC, together with its higher heat-sensitivity compared to Normal-Strength Concrete – NSC [5].

The idea that pore pressure plays an important role in triggering spalling is corroborated by the beneficial effect commonly observed when polypropylene (pp) fibre is added to the concrete mix. Limited amounts of pp fibre (1-2 kg/m$^3$) are sufficient to significantly reduce the likelihood of spalling, probably thanks to three main processes: (a) further porosity because of fibre melting at 160-170°C [3], additional microcracking in the cement paste due to (b) the thermal dilation of melting fibre [3] and (c) to the stress intensification around the edges of the channels left free by melted fibre [6].

In order to cast some light on spalling phenomenon, however, the evaluation of thermal stress and pore pressure is not yet sufficient, since the conditions of spalling initiation and propagation, as well as the progression of the detachments need to be monitored. The quantification of spalling time, depth and extension during a fire is, however, difficult, since most of the available techniques can be hardly implemented in the test furnace.

In the present paper, approaches based on Ultrasonic Pulse-Echo (UPE) and Ground-Penetrating Radar (GPR) are discussed. Other examples of Real-Time survey during fire tests can be found in the literature, mostly based on Acoustic Emission (AE), which proved to be rather effective even though distinguishing micro- and macro-cracking from spalling is rather difficult [7,8].

UPE and GPR have been considered within a research project recently finalized at Politecnico di Milano (Milan, Italy) in collaboration with CTG-Italcementi Group (Bergamo, Italy) [9]. The experimental campaign was focused on concrete slabs (800x800x100 mm) subjected to heating at the bottom face according to the Standard Fire curve, while a biaxial membrane loading was applied in order to instate a mean compressive stress of 10 MPa. Slabs were uniformly heated at the intrados via propane burner and loading was implemented by 8 hydraulic jacks restrained by a steel frame. It is worth noting that the slabs were heated only in the central 600x600 mm area, in order to preserve the hydraulic jacks with a 100 mm unheated concrete belt. In order to limit the confining effect provided by the colder belt, 16 radial cuts were performed. In Fig.1a the loading system (8 hydraulic jacks + restraining steel frame) is shown above the furnace, while in Fig.1b the specimen geometry is reported together with the location of UPE and GPR measurements.

A total of 4 concrete mixes were designed (f$_c$$\geq$ 60 MPa; calcareous aggregate) and 2 slabs per mix were cast. The mixes differed only by fibre addition: (1) no fibre, (2) 40 kg/m$^3$ of steel fibre, and 2 kg/m$^3$ of (3) monofilament or (4) fibrillated polypropylene fibre.

The abovementioned Real-Time survey techniques were implemented during the tests at the cold face, where the relatively low temperature (T $\leq$ 150°C) allowed to use the instrumentation, even if just for a short time. The different approaches and results are discussed in the following.

Figure 1. Spalling test on concrete slabs subjected to Standard Fire at the intrados under biaxial membrane loading: (a) loading system on the furnace, and (b) specimens geometry and location of UPE and GPR measurements.
2. Real-time survey during fire tests

2.1 Ultrasonic Pulse-Echo – UPE

As well known, the UPE method exploits the reflection/refraction of ultrasonic pulses propagating within a medium. The evaluation of the reflection (echo) time in correspondence of discontinuities, allows to define void position inside continua or thickness of discrete elements [10] (see Fig.2a). When an ultrasonic source emits pulses on the surface of a member, the elastic waves propagate through the continuum. If a discontinuity or change in acoustic impedance is crossed (for instance due to the sudden variation of material properties or to the interface between two layers), elastic waves are partially transmitted and partially reflected, according to the contrast of acoustic impedance (the higher the stiffness and density, the higher the acoustic impedance). In particular, if reflection occurs due to an impedance reduction, the amplitude sign reverses.

In concrete members, a very important case is met when discontinuity is represented by air, which exhibits the (practically) total reflection accompanied by the wave sign reversal, since air has a negligible stiffness for both compression and shear elastic waves. This is the reason why UPE shows to be rather effective in detecting delaminations and voids in concrete members [11,12].

The ultrasonic source can be a mechanical impact of small hammers or metallic balls (namely, Ultrasonic Impact-Echo) or pulses produced by ultrasonic transducers (namely, Ultrasonic Pulse-Echo) [13]. In the latter case, both compression and shear waves can be used. Post-processing of data can be performed in the frequency domain through the Fourier Transform, as well as in the time domain by determining the arrival time of the reflected wave at the receiver or by using other approaches based on coda waves, and Wavelet or Hilbert Transforms [14]. Spectrum analysis, however, requires to eliminate “parasitic” effects caused by the global excitation of the specimen and by edge-effects [15].

In the present case, the ultrasonic flaw detector A1220 by Acoustic Control Systems was used, fitted with the M2502 shear pulse emitter/receiver array (Fig.2b). In Fig.3a the typical ultrasonic waves reflected at the intrados (heated face) and observed at the receiver are shown for different fire durations. The coloured dot highlights the time shift of a reference peak during heating. At high temperature, in fact, the decay of the mechanical properties of concrete reduces its stiffness so making the ultrasonic waves slower. This yields to a delay in the reflection time at the slab intrados. The decrease of acoustic impedance at the exposed face tends also to reduce the amplitude of the reflected wave.

On the contrary, when spalling occurs, a sudden decrease in concrete thickness takes place and the time of reflection instantaneously decreases (echo advance in Fig.3a). Such sudden decrease is considered in assessing the spalling depth. This, however, requires a preliminary evaluation of the slowness profile (namely 1/velocity) along the slab thickness, which may be worked out once the temperatures within the concrete slab and the decay of ultrasonic wave velocity due to heating are known.

Figure 2. (a) Ultrasonic Pulse-Echo principle and (b) adopted ultrasonic device placed on the slab.
Figure 3. Ultrasonic Pulse-Echo method: (a) waves at the receiver showing the echo delay increase due to heating and the sudden decrease due to spalling; intensity graph of (b) wave signals (together with the peak of the Hilbert Envelope in white dots) and (c) Frequency Spectrum of the received waves as a function of fire duration; (d) relative Echo Delay – ED according to the 3 approaches (Time Scale, Hilbert Envelope and Frequency Spectrum) for the slab Fibrillated B and (e) according to the Time Scale for 4 tested slabs (1 per mix); (f) comparison among the ultrasonic pulse velocity obtained via inverse analyses and that measured in residual conditions on unstressed specimen; and (f) ED evaluated via UPE and Slowness Integration for slab Plain B.
In the case at hand, the thermal field was known thanks to the continuous measurements of temperature at intrados, extrados and at 6 different depths during heating.

The decay of the compression ultrasonic wave velocity with temperature was evaluated in a previous experimental campaign, conducted on the same concrete mixes on unstressed cylindrical specimens in residual conditions (Fig.3f). If the Poisson ratio is known, the shear wave velocity can be evaluated starting from the compression wave velocity. At high temperature, however, different aspect should be taken into account: (a) concrete mechanical properties (and, hence, reasonably acoustic impedance) measured after heating and cooling (residual conditions) are generally lower than at high temperature (hot conditions) due to the further damage brought in by cooling; (b) material damage is lower if a limited compression is applied during heating, and, finally, (c) the Poisson ratio can change – even significantly – with temperature.

In the case at issue, UPE was implemented during heating, adopting shear waves on concrete subjected to compression, while the ultrasonic investigations of the previous experimental study were performed after cooling, adopting compression waves on unstressed specimens. This is the reason why a significantly lower decrease of the pulse velocity is expected to take place in the slabs, with respect to that obtained on cylindrical specimens.

To overcome such problem, an inverse analysis was implemented, aimed at evaluating the ultrasonic shear pulse slowness profiles during fire exposure. The material slowness as a function of temperature was expressed via a polynomial function (cubic interpolant) whose coefficients were determined so to minimize the difference between the observed reflection times (or echo delays) and the slowness integrals in the whole set of steps preceding spalling (if any).

When spalling occurs, the reduction in the reflection time observed via UPE is used to evaluate the spalling depth, by looking for the thickness reduction necessary to make the reflection time computed through slowness integration equal to that measured via UPE (Fig.3g).

The last crucial point is the identification of the Echo Delay – ED, namely the shift of the arrival time of the wave reflected at the intrados. Different approaches can be used, by working either on time or frequency domain. In the former case, one option is to rescale the time axis of the first acquired waveform until a significant indication (in general the time window 90-120 µs) shows the best correlation with its counterpart in the subsequent waveforms (the probe offset time has been taken as a fixed pivot point). This implies a Time Scale dilation which reflects the average increase of slowness across the slab thickness. The same concept may be more easily implemented by tracking the peak of the Hilbert envelope transform [16], though the sharper attenuation of the echo onset due to concrete deterioration tends to further delay this indicator, leading to some overestimate for long fire exposures.

A similar approach can be implemented in the frequency domain, since the dilation of the signal timescale translates into a contraction of the spectrum, which can be tracked by monitoring the variation of some reference peaks. As abovementioned, the heat-induced damage in concrete makes waves slower, this leading to an increase of the echo delay and to a decrease of the frequency peaks (the rate of peak-frequency decrease is the inverse of relative increase of the arrival time). Since the Time Scale method exhibited a marginally better repeatability among the tests, it has been taken as a reference in the following.

In Figs.3b and c, the intensity graphs of the wave signals and of the frequency spectrums are shown, for plain concrete slab (Plain B) as a function of fire duration. It can be observed that the evolution of frequency peaks can be hardly followed after spalling.

In Fig.3d the increase of echo delay evaluated according to the 3 methods is shown for slab Fibrillated B, highlighting their general good agreement, with the exception of the Hilbert envelope method for long fire exposure.
The relative increase of the echo delay time obtained via the Time Scale method for 4 different slabs (1 per mix) is reported in Fig. 3e, showing a remarkable repeatability among the tests. In Fig. 3f, the decay of ultrasonic pulse velocity obtained via inverse analysis on the basis of the echo delay time evaluated via the Time Scale method are compared with those obtained in the previous experimental campaign on unstressed cylindrical specimen. As expected, a more significant damage affects this latter type of specimens. Finally, the comparison between the experimental trend of the echo delay in test Plain B and the numerical values obtained by slowness integration is reported in Fig. 3g, showing a satisfactory match both during the smooth damage due to heating and after the sudden detachment of the spalled layer. The actual spalled thickness measured after the test was 40 mm which is in fairly good agreement with the layer to be deleted in the slowness integration (35 mm).

2.2 Ground-Penetrating Radar – GPR

Ground-Penetrating Radar (GPR) is a non destructive geophysical technique based on the study of the propagation of electromagnetic waves and their reflections through a material or a fluid. GPR is a well known and established method especially in the field of structure inspections and building diagnosis [17-19]. The material property governing electromagnetic wave velocity is the dielectric constant [20,21], which is defined as the ratio between the electric permittivity of the material at hand and of air. It is worth noting that air and water have very low and very high dielectric constant, respectively, so making dielectric properties of concrete strongly influenced by air and moisture contents [22,23].

In particular, water content causes an increase in both the polarization mechanism and the real permittivity (with an increase of the dielectric constant by even more than two times going from dry to saturated concrete [24]). The former effect induces a decrease of the electromagnetic energy, hence to a reduction on reflected-wave peak amplitude [25-27], while the latter causes a delay of the reflection time (because of travel time increase). Thanks to these aspects, good results in monitoring water content and saturation in concrete have been shown in the literature [24,28,29].

Similarly to the ultrasonic pulses, electromagnetic waves propagating through a continuum are partly reflected and partly refracted when a sudden change in electric properties is met. The travel time of reflected waves can be used to evaluate layer thicknesses or defect depths, as already discussed for UPE. In 2 of the 8 slabs described in the Introduction, linear scans have been acquired during the fire tests, with the characteristics reported in Table 1. The equipment was an IDS (Ingegneria dei Sistemi, Italy) georadar system with a central frequency and a bandwidth of 3GHz (Fig. 6a). The two dipoles are 6 cm-spaced and oriented orthogonally to the acquisition direction. The processing steps applied on the datasets are described in Table 2.

Bidimensional slices for the slab made in polypropylene fibre concrete (Monofilament B) are shown in Fig. 4. In each frame the geometrical limit of the slab are indicated, as well as the rising water level. From the processed data, two major features can be highlighted. The water front, marked with the blue tag in Fig. 4, is clearly detected by the blurring in the lower part of the concrete slab. This effect is related to the energy absorption of water, which reduces the amount of energy arriving at the end of the slab and returning back. The second interesting aspect is the variation of the propagating speed of the wave. The presence of a water-clogged interface modifies the total travel time of the wave, approximately increasing the velocity by 25% and therefore changing the perceived slab thickness. This is easily visible in the last frames (hence, for long fire durations). The commented outcomes have been confirmed also in the second test performed on plain
concrete slab (Plain B), whose processed radargrams are shown in Fig.5. In this case the presence of water is more evident, always in terms of second background blurring and time-moving interface. Differently from the previous case, its effect does not propagate into a variation of the wave speed, as the picked slab boundaries remains in their initial location. As concern this last aspect, however, it is worth noting that after 35 min of heating, the test was stopped due to the severe damage caused by spalling.

Table 1. Features of the profile acquisition.

<table>
<thead>
<tr>
<th>Slabs</th>
<th>Profile timing</th>
<th>Number of profiles</th>
<th>Profile length [cm]</th>
<th>Inline sampling [cm]</th>
<th>Sampling period [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monofilament B</td>
<td>10 minutes</td>
<td>12</td>
<td>30</td>
<td>0.6</td>
<td>0.014</td>
</tr>
<tr>
<td>Plain B</td>
<td>10 minutes</td>
<td>18</td>
<td>50</td>
<td>1.0</td>
<td>0.011</td>
</tr>
</tbody>
</table>

Table 2. Processing steps applied on the datasets.

<table>
<thead>
<tr>
<th>Processing step</th>
<th>Time calibration</th>
<th>Frequency filtering</th>
<th>Time window</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Time shift with maximum picking scheme</td>
<td>Zero-phase Butterworth filter</td>
<td>Data windowing</td>
</tr>
<tr>
<td></td>
<td>Frequency range 0.9 – 3.2 GHz</td>
<td>Time limit 3 ns</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4. GPR results on polypropylene fibre concrete slab (Monofilament B) for different fire durations. White and black flags represent the upper and the lower limit of the slab, respectively, while blue tag marks the rising waterfront.
The water front in the two slabs is reported in Fig.6b as a function of the fire duration. It turns out that in the case of explosive spalling (concrete slab Plain B) the final position of the saturated layer matches with the incipient fracture plane, confirming the crucial role of moisture transient in this complex phenomenon.

Figure 5. GPR results on plain concrete slab (Plain B) for different fire durations. White and black flags represent the upper and the lower limit of the slab, respectively, while blue tag marks the rising waterfront.

Figure 6.(a) Picture of the device used and (b) water front position according to the radiograms of Figs.5 and 6.
3. Conclusions

A set of 8 concrete slabs have been recently tested at the Politecnico di Milano, in order to investigate the influence of many parameters on spalling sensitivity in fire. The specimens were heated at the bottom side according to the Standard Fire curve, while a constant biaxial compression membrane load was applied through hydraulic jacks. On 6 of the 8 tests, spalling monitoring was implemented via well-known Non-Destructive Techniques, namely Ultrasonic Pulse-Echo (on 6 slabs) and Ground-Penetrating Radar (on 2 slabs).

The combination of these two methods, together with the continuous measurement of temperature and pressure along the depth of the specimens, provided very important information about spalling onset time, detachment depth and moisture front position. Ultrasonic Pulse-Echo showed to be rather effective in evaluating concrete damage at high temperature and in determining spalling depth, while Ground-Penetrating Radar was able to detect the water front in order to relate its position with the plane of spalling initiation.

The assessment of concrete damage induced by the combined effect of temperature and load through the post-processing of Ultrasonic Pulse-Echo measurements is something new with respect to the results found in the literature, since ultrasonic investigation on heat-damaged concrete is usually performed after cooling (residual conditions) and in unstressed specimens. Further studies have been planned, focused in determining the decay of ultrasonic pulse velocity at high temperature for different values of compression stress. A new Research Project is in progress at Politecnico di Milano in collaboration with the Centre Scientifique et Technique du Bâtiment – CSTB, Marne la Vallée (France), based on the same test set-up herein discussed, in which nominally identical slabs will be subjected to 4 different levels of stress, during heating. GPR, on the other hand, proved to be capable in detecting the rising water front with a significant resolution and in monitoring its status, in terms of widespread and height of climb.

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