Pulse-Echo Monitoring of Concrete Damage and Spalling during Fire

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ABSTRACT

Monitoring concrete damage and spalling progression in structural members during fire tests (hot conditions) is a central but challenging task, since the high temperatures involved make difficult the implementation of most of the common Non-Destructive evaluation methods. Hence, an advanced ultrasonic technique – Ultrasonic Pulse-Echo (UPE) – was recently adapted for real time survey in fire test, in order to evaluate the material damage during heating. The UPE technique was implemented at the cold (upper) face of concrete slabs (800x800x100 mm) heated at the bottom face according to the Standard Fire and subjected to biaxial compressive membrane loading. Different concretes were tested, with grades ranging from 40 to 60 MPa, with and without different kinds of fibre (monofilament or fibrillated polypropylene, or steel fibres). Furthermore, different load levels were applied, from 0 to 25% of the original compressive strength. During tests, spalling was generally observed in loaded plain concrete (up to 50-60 mm depth), while only slight scaling was experienced on unloaded samples or if polypropylene fibre was added. The method proved to be very effective in recognizing the decay of the Ultrasonic Pulse Velocity (UPV) with temperature and the role played by external loading and fibre type.

INTRODUCTION

Concrete generally exhibits a satisfactory behaviour in fire thanks to its incombustibility and low thermal diffusivity which allows to maintain relatively low temperature in the inner layers, even for long fire durations. A proper design of reinforced concrete structures, however, requires the correct knowledge of material behaviour in order to optimize member sections and mix design accordingly to the needed fire resistance. Unfortunately, concrete response at high temperature is not easy to investigate due to the influence of different aspects such as the dependency of material decay on stress level and fire stage (hot and residual conditions), and spalling phenomenon.

Thermal damage in concrete, in fact, is influenced by the state of stress, since it has been proved that a lower damage is produced if a low/moderate compression is applied during heating. This is probably caused by the reduction of the tensile

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stress brought in the cement matrix by the dilation of the aggregate. In addition, there is a difference in the material properties decay between hot and residual conditions because of the further damage introduced by cooling.

Finally, spalling can significantly influence the structural behaviour. Such phenomenon consists in the more or less violent expulsion of chunks from the exposed face and is made particularly complex by the mutual interaction of different influencing factors, namely heating rate, moisture content, pore pressure and stress [1-4]. Spalling ensues from the simultaneous action of: (a) stress induced by thermal gradients and external loads and (b) pore pressure rise caused by water saturation and vaporization.

High-Performance Concrete (HPC) is generally more prone to spalling compared to Normal-Strength Concrete (NSC) due to its denser matrix (that favours higher values of pore pressure) and its higher heat-sensitivity [5]. The common way to reduce spalling risk is to add polypropylene (pp) fibre (1-2 kg/m^3), whose beneficial effect is provided by the further porosity induced by melting and stress intensification around the edges of the channels left free by melted fibres [3,6].

It is worth noting that monitoring the conditions of spalling initiation and propagation, as well as the progression of detachments in fire tests, should be of primary importance in order to fully understand such phenomenon. 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 the approach based on Ultrasonic Pulse-Echo (UPE) is 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 has 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. 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 rim. In order to limit the confining effect provided by the colder boundary, 16 radial cuts were performed. A section view of slab and loading system (8 hydraulic jacks + restraining frame) above the furnace is shown in Fig.1a, while the specimen geometry is reported in Fig.1b, together with the location of UPE measurements, pressure gauges, thermocouples and displacement transducers.

Firstly, 4 concrete mixes were investigated ($f_c \approx 60$ MPa; calcareous aggregate). The mixes differed only in 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. Secondly, also ordinary concrete was studied ($f_c \approx 40$ MPa; calcareous aggregate). The abovementioned Real-Time survey technique was implemented during the tests at the cold face, where the relatively low temperature ($T \leq 150$°C) allowed using the instrumentation.

ULTRASONIC PULSE-ECHO – UPE

The UPE method is based on the reflection/refraction of ultrasonic pulses when crossing a discontinuity within a medium. As shown in Fig.2a, when an ultrasonic source emits pulses on the surface of a member, the elastic waves propagate through the continuum. When a discontinuity is reached, such as a sudden variation of material properties or an interface between two layers, elastic waves are partly transmitted and partly reflected, according to the contrast of acoustic impedance (*acoustic impedance* = *density* x *wave velocity*).

In particular, if reflection occurs due to an impedance reduction, the amplitude sign reverses. A special case is represented by air gap inside concrete. In this case total reflection is observed together with wave sign reversal due to the negligible density and velocity for both compression and shear elastic waves in air. This makes UPE very sensitive to delaminations and voids in concrete members [10,11,12].

As ultrasonic source, a mechanical impact of small hammers or metallic balls (namely, Ultrasonic Impact-Echo) or pulses produced by ultrasonic transducers (namely, Ultrasonic Pulse-Echo) can be used [13]. In the latter case, both compression and shear waves can be generated. Post-processing of data is often non trivial due to the possible influence of the boundary conditions in the propagation of direct and reflected waves. Data can be analyzed 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 Wavelet or Hilbert Transforms [14]. Spectrum analysis, however, requires eliminating "parasitic" effects caused by the global excitation of the specimen and by edge-effects [15].

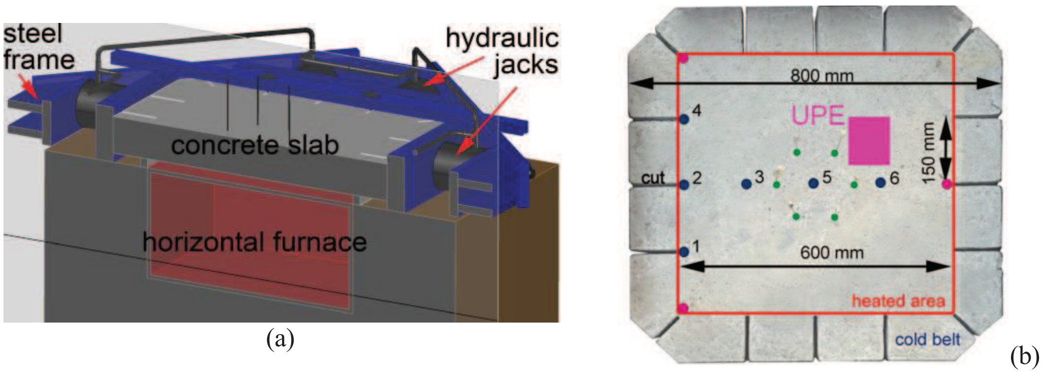

Figure 1. Spalling test on concrete slabs subjected to Standard Fire at the intrados under biaxial membrane loading: (a) slab and loading system on the furnace, and (b) specimens geometry and location of UPE (green dots = pressure gauges and thermocouples, blue dots = displacement transducers).

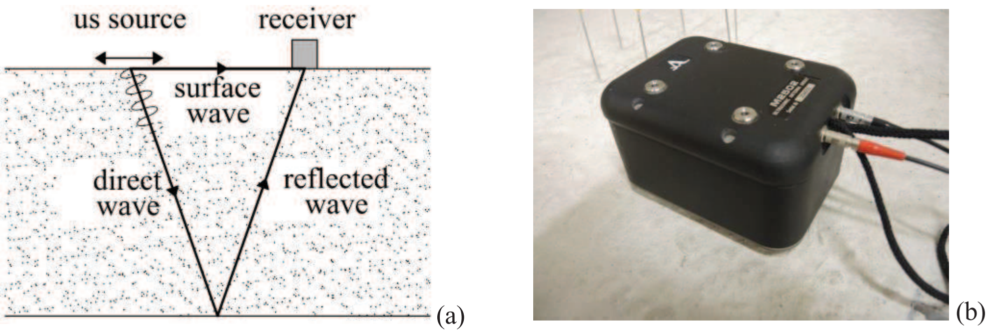

Figure 2. (a) Ultrasonic Pulse-Echo principle and (b) adopted ultrasonic device placed on the slab.

In this research, 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 in a test on plain HPC. In this test, spalling occurred with a single violent event after 35 min of heating.

A reference peak is chosen and highlighted by means of a coloured dot in each wave. By observing the 3 curves related to the measurements before spalling occurred, it is clear that the arrival time of the reference peak at the receiver increases during the test (*time shift* or *echo delay*). This delay takes place, since wave propagation becomes slower due to thermal damage. A reduction of the reflected pulse amplitude is also observed, due to the increased wave attenuation and reduced contrast of acoustic impedance at the exposed face of the slab.

When spalling occurs, on the contrary, a sudden decrease in concrete thickness takes place and the time of reflection instantaneously decreases (echo advance in Fig.3a). Once the echo advance is determined, the spalling depth can be estimated if the pulse velocity (or slowness = 1/velocity) in damaged concrete is known. This requires a preliminary evaluation of the slowness profile along the slab thickness. 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, while the ultrasonic pulse velocity decay with temperature was not known a priori.

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.3d). At high temperature, however, two main aspects should be taken into account: (a) concrete mechanical properties (and, hence, 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; and (b) material damage is lower if a moderate compression is applied during heating.

This consideration explains why the ultrasonic investigations of the previous experimental study performed after cooling on unstressed specimens cannot be used, since a significantly lower decrease of the ultrasonic pulse velocity is expected to take place in the slabs.

To overcome such problem, an inverse analysis was implemented, aimed at evaluating the ultrasonic shear pulse slowness profiles during fire exposure. This was carried out by defining the material slowness as a function of temperature by means of a polynomial function (cubic interpolant), whose coefficients can be 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). The integration of the slowness profile in the depth, in fact, is equal to the time required by ultrasonic waves to cross the slab thickness.

When spalling occurs, the reduction in the reflection time observed via UPE (Fig.3e) is used to evaluate the spalling depth, by determining the thickness reduction required to obtain the same reduction of the slowness integral.

The last crucial point is the precise identification of the Echo Delay – ED, namely the shift of the arrival time of the wave reflected at the intrados. Different procedures have been studied in order to check their sensitivity and effectiveness in defining the ED and the readiness for automation.

Post-processing can be worked out 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].

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 frequency 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). Such methods are suitable to evaluate an average slowness decay relative to virgin conditions. Since the Time Scale method exhibited a marginally better repeatability among the tests, it has been taken as a reference in the following (further details are given in [17]). Another approach is based on defining the time delay of arrival of the reference peak, providing results in terms of time (μs) and making easier the following evaluation of the spalling depth.

The first set of tests was performed on 4 slabs made of 4 concrete mixes with the same concrete grade and aggregate type ($f_c \approx 60$ MPa, silico-calcareous aggregate) but different fibres (no fibre, steel fibre in the content of 40 kg/m^3 and monofilament or fibrillated polypropylene fibre in the content of 2 kg/m^3). In all cases, the applied membrane compressive stress was 10 MPa. In Fig.3b the increase of echo delay evaluated according to 3 methods is shown for slab Fibrillated B, highlighting their general good agreement, with the exception of the Hilbert envelope method.

The relative increase of the echo delay time obtained via the Time Scale method for the 4 different slabs is reported in Fig.3c, showing a remarkable repeatability among the tests. In Fig.3d, 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 in residual conditions. 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.3e, showing a satisfactory match both during the smooth damage due to heating and after the sudden detachment of the spalled layer. The total 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).

In the framework of a joint research project with the Centre Scientifique et Technique du Bâtiment – CSTB, Marne la Vallée (France), a second set of tests was performed on 4 nominally identical slabs made of NSC ($f_c \approx 40$ MPa, calcareous aggregates), but with 4 different levels of biaxial membrane stress (0, 0.5, 5 and 10 MPa), in order to investigate the influence of load on spalling phenomenon and on the decay of ultrasonic pulse velocity with temperature.

Severe spalling was observed for stress levels of 5 and 10 MPa (more than 50 mm of spalling depth), medium spalling depth for 0.5 MPa (about 20 mm) and no spalling for unloaded specimens. Spalling took place after about 8 min of heating. In Fig.4 the results of UPE measurements are reported in terms of Time Shift with respect to the

Reflection Time in virgin conditions. For fire durations shorter than 8 min (before any spalling occurred), a slower increase of time delay is observed for higher values of applied load. This means that the thermal damage depends also on the load level, since it decreases with the applied compression (at least for the investigated range: 0-0.25 f_c).

After spalling occurred, the comparison among the tests becomes more difficult because the decrease of Time Shift observed for 0.5, 5 and 10 MPa is caused by the reduction of thickness, and the results are no more directly comparable in terms of Time Shift. The above described effect agrees with many results in the literature which show as the decay with temperature of the mechanical properties of concrete (both strength and stiffness) are lower if compression is applied during heating.

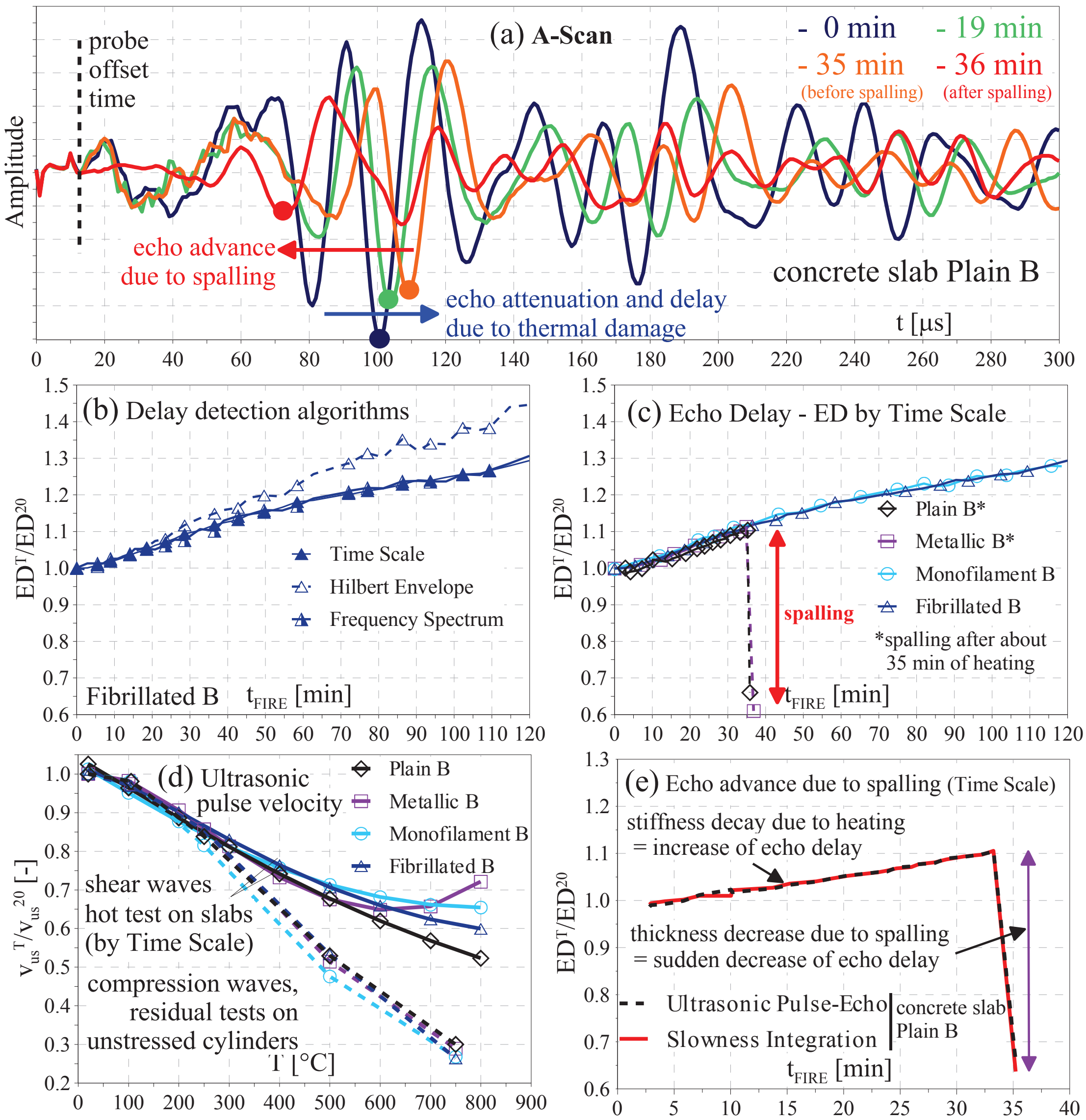

Figure 3. Ultrasonic Pulse-Echo method: (a) waves at the receiver showing the echo delay increase due to heating and the sudden decrease due to spalling; (b) relative Echo Delay – ED according to 3 approaches (Time Scale, Hilbert Envelope and Frequency Spectrum) for the slab Fibrillated B and (c) according to the Time Scale for 4 tested HPC slabs (1 per mix); (d) comparison among the ultrasonic pulse velocity obtained via inverse analyses and that measured in residual conditions on unstressed specimens; and (e) ED evaluated via UPE and Slowness Integration for slab Plain B.

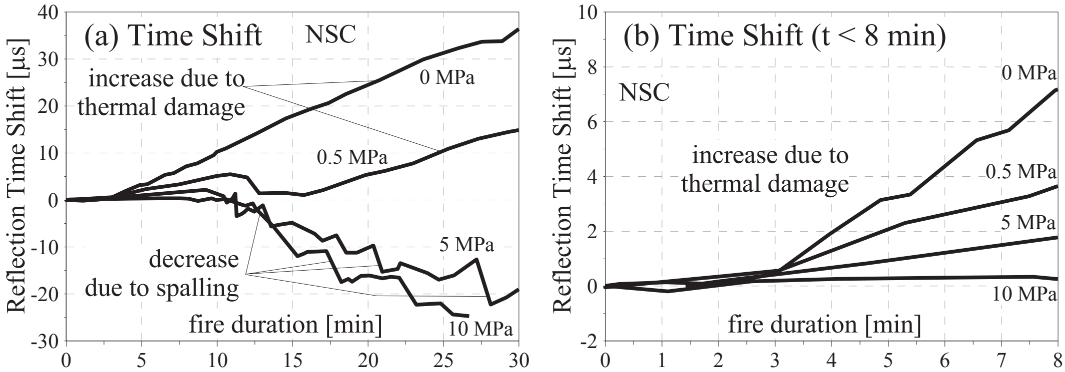

Figure 4: Reflection Time Shift for 4 levels of membrane stress as a function of fire duration: (a) full plot, and (b) plot for t ≤ 8 min.

This is probably due to the smoothing of the tensile stress induced in the cement paste by aggregate dilation (cement paste-aggregate kinematic incompatibility).

CONCLUDING REMARKS

Two sets of 4 concrete slabs have been tested at the Politecnico di Milano, in order to investigate the influence of different parameters on spalling sensitivity in fire. The specimens were heated at the bottom side according to the Standard Fire curve, while a constant biaxial membrane compression was applied through hydraulic jacks. Spalling monitoring was implemented via an established Non-Destructive Technique, namely Ultrasonic Pulse-Echo. This method, together with the continuous measurement of temperature along the depth of the specimens, is shown to be rather effective in evaluating concrete damage at high temperature and in determining spalling depth.

The original feature allowed by proper post-processing of Ultrasonic Pulse-Echo measurements is the assessment of concrete damage induced by the combined effect of temperature and load. This is something new compared to the results available in the literature, since ultrasonic investigation on heat-damaged concrete is usually performed after cooling (residual conditions) and in unstressed specimens. The investigations clearly show as the decay of ultrasonic pulse velocity with temperature in hot conditions can be significantly lower than in residual conditions; moreover it was proved as the higher the compression stress applied during heating, the lower the thermal damage. These results come together with the effective monitoring of spalling depth during fire tests, a not easy task due to the high temperatures involved.

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