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ASSESSMENT OF FIRE DAMAGE IN CONCRETE STRUCTURES: NEW INSPECTION TOOLS AND COMBINED INTERPRETATION OF RESULTS

R. Felicetti

Dept. of Civil and Environmental Engrg - Politecnico di Milano, Milan (Italy)
email: roberto.felicetti@polimi.it

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Abstract. *The assessment of fire damage in concrete structures involves two complementary major tasks: on-site investigation and interpretation of the observed evidences. Concerning the first point, some innovative and viable inspection techniques are briefly illustrated in the paper. Their common trait is the ability to provide an immediate feedback, with no need for time-consuming laboratory analyses. As for the interpretation of results, the main issue is to harmonize the information provided by the available diagnostic tools, which is limited to specific ranges of temperature and to definite depths in the exposed concrete cover. The proposed approach relies on the parametric analysis of the compartment temperature developed in a set of realistic fire scenarios. The resulting temperature profiles are then checked against the results of the Non-Destructive inspection techniques, in order to select the most likely thermal input undergone by the structural members.*

1 INTRODUCTION

The assessment of the post-fire bearing capacity and durability of concrete structures is a complex and still open issue involving different areas of expertise, from Material Science to Structural Engineering, from Non-Destructive Testing to Fire Engineering. Developing new tools for the material inspection and devising new procedures for the interpretation of the test results are the two key aspects to be addressed in order to allow a substantial progress in this field.

The first step in the evaluation of fire damage implies a thorough inspection of the structure at different scales [1]: global (fire scenario, irreversible deformation of members), intermediate (cracks, spalling and rebar buckling within the cross-sections) and local (material identification in specific points). An overview on the established approach to the problem can be found in a couple of recognized technical publications on the assessment and repair of fire damaged structures [2, 3].

At the smallest scale of observation, the challenging issue is represented by the strong variability of the material condition at different depths from the heated surface. Due to the steep thermal gradients that develop during a fire, the concrete cover has to be regarded as a strongly layered stratum. This applies to the mechanical response (compressive and tensile strength, Young's modulus, hardness, velocity and attenuation of elastic waves) as well as to a number of physicochemical properties that are markedly affected by the exposure to high temperature (density of micro-cracks, porosity, humidity, chemical composition, colour, electric conductivity, etc.) [4, 5].

Many dedicated methodologies have been proposed for tackling the problem of material identification at this local scale [6]. Unfortunately, most of them rely on demanding laboratory analyses to be repeated on small samples taken at different depths within the cover (e.g. thin disks cut from a core). As a first tentative to go beyond this limitation, some innovative and viable inspection techniques were proposed by the author at the 4th SiF workshop (simplified interpretation of Ultrasonic Pulse refraction, discoloration measurement based on a digital camera and monitoring of the drilling resistance) [7]. Their common feature is the ability to provide an immediate feedback on the material condition, allowing to direct any further test on the structure being inspected. In recent years, other methods have been developed in the same perspective: the hammer drill pulse transmission (far more sensitive than the original drilling resistance method) [8], the chemo-physical analysis of the drilling powder (not requiring any sample preparation) [9] and the dynamic hardness of rebars (addressing the residual capacity of the reinforcement) [10]. A brief account on these methods is provided in the first part of this paper.

Despite of the wide range of available inspection tools, it has to be remarked that in most cases the information they provide is limited to specific ranges of temperature (or damage) and to definite depths within the exposed concrete cover. Combining different techniques is then essential to offset these restrictions, improving the reliability of the results. This requires a coordinated comparison of different indications against the possible temperature profile. The latter is the result of the temperature developed in the compartment, whose impact is smoothed by heat conduction in the exposed structural members.

In some regards, concrete elements in fire respond by both filtering the thermal input from the compartment and mapping the maximum experienced temperatures, by way of the physicochemical transformations occurring in the material. Even if not all the parameters governing the fire scenario are accurately known (fire duration, maximum temperature, decay rate, etc.) a parametric analysis can be performed, in order to produce a set of possible temperature profiles within the member, to be validated by checking their consistency with the experimental results. Besides allowing to merge the results pertaining to different temperature ranges and different depths, in the end a fire scenario of realistic severity is validated, extending the significance of results well beyond the inspected members. This kind of approach is discussed in the second part of the paper.

2 NEW INSPECTION TOOLS FOR MATERIAL ASSESSMENT

The assessment of the residual condition of fire damaged concrete can take advantage of a number of available tools [1]. They range from well established and relatively simple techniques (e.g. chiselling, surface hardness) to rather sophisticated test methods (surface waves, pulse refraction) or thorough laboratory analyses (sliced-core examination). However, in-situ viability, quickness and reliability are important requirements they fail to harmonize in most cases. Keeping this in mind, some innovative techniques for the material assessment at the local scale have been proposed by the author in recent years. A brief summary of their pros and possible limitations is given in the following.

2.1 Hammer drill pulse transmission

Monitoring the resistance encountered while drilling the concrete cover (time and work spent for a unit advance of the bit) is an effective method for post-fire in situ investigation [7]. The technique is very quick (about 10s per test) and not influenced by possible cracks or surface roughness due to spalling. On the other hand, the above drilling resistance indicators are not very responsive to mild fire damage, since a decrease is recognized just for a compressive strength decay exceeding 50%. Moreover, the local disturbance due to the hard coarse-aggregate pebbles require to average some tests for recognizing a clear trend in the material response.

To overcome these limitations, a new version of the drilling technique has been developed [8], taking

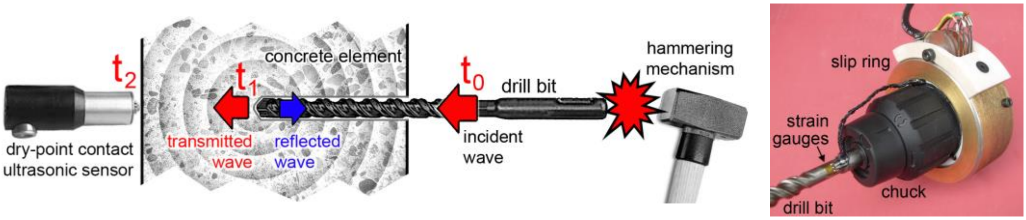

Figure 1. Working principle of the Hammer-Drill Pulse Transmission method and bit-strain measuring system.

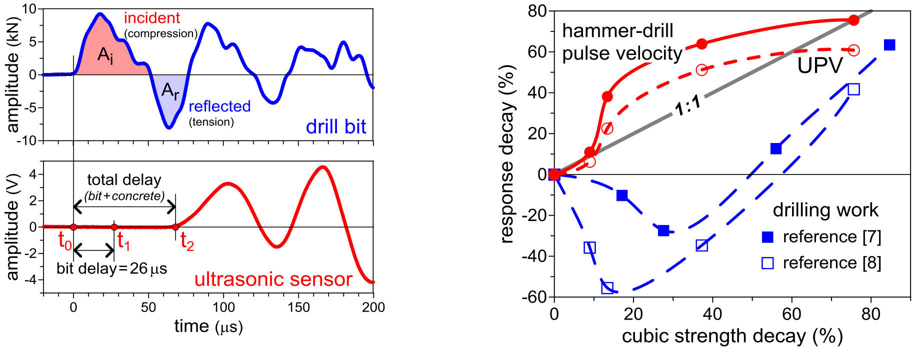

Figure 2. Time of flight of one hammer-drill pulse and sensitivity to thermal damage of the pulse velocity compared to the drilling work (UPV = conventional Ultrasonic Pulse Velocity).

inspiration from the Seismic While Drilling methods that are commonly used in geophysical surveys. In this case, the strong compressive pulses generated by the hammering mechanism of the drill are monitored, with the objective of measuring their time of flight to a fixed receiver positioned opposite to the drilled side of the member (pulse velocity scan, Fig. 1). The implementation of this principle implies some technicalities, like strain gauges glued on the bit shank, a slip ring for signal transmission (Fig. 1), a wide-band bridge-amplifier and a USB scope.

Thanks to the relatively low frequency of the excited waves (~ 15 kHz, i.e. wavelength ~ 0.3 m), the method is not influenced by the coarse aggregate and can be applied to strongly damaged and rather thick members. A series of calibration tests on uniformly damaged concrete cubes (150 mm side, original strength $f_{c,cube} = 52$ N/mm^2) showed a very good sensitivity in the whole range of interest (Fig. 2), with the same trend as the well established Ultrasonic Pulse Velocity test. Nonetheless, the potential of the method becomes evident when dealing with damage gradients. In the case of a concrete panel made of the same concrete and heated on just one side (thickness = 135 mm, T_{max} = 840-120°C), the intensive monitoring of the drilling process (10-20 pulses/mm) allows to produce a detailed profile of the residual pulse velocity (Fig. 3). Also the repeatability of results is to be remarked.

Further studies are in progress, aimed at the interpretation of results in case of indirect transmission (drill and sensor on the same side), that is a relevant issue in case of single-sided access to the inspected member (e.g. walls, slabs and tunnel linings).

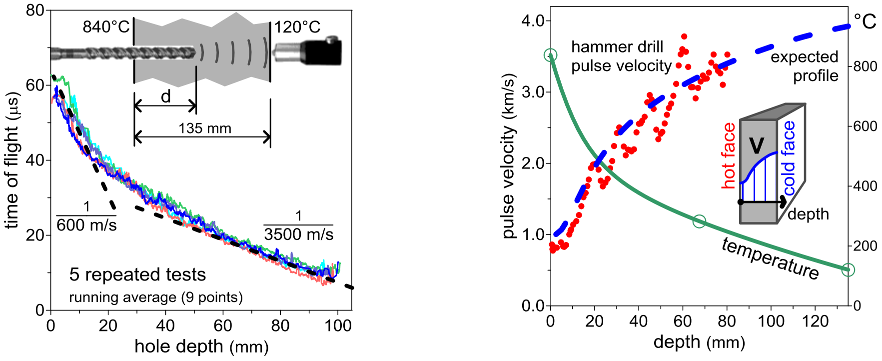

Figure 3. Time of-flight of pulses to the ultrasonic receiver in a thermally damaged concrete panel and profile of the pulse velocity through its thickness.

2.2 Analysis of sorted samples of drilling powder

A number of physico-chemical analyses suitable for the local condition assessment of fire damaged concrete require a preliminary grinding of the material into a fine powder (X-ray diffraction, thermo-luminescence, Differential Thermal Analysis DTA, Thermo-Gravimetric Analysis TGA, etc.). Moreover, some tests that are normally performed on intact samples, may be in principle carried out also on the pulverized material (carbonation depth, colour measurement, etc.). This evidence casts the base for merging the results of the drilling test and the following examination of the ensuing powder.

In the problem at issue, characterized by steep variations of the investigated properties with the drilling depth, an important requirement is to preserve the order of extraction, so to trace the original location of the powder. A special device has been developed to this purpose (Carbontest®, www.carbontest.it), which allows the continuous collection of the ground-concrete streaming through the helical flutes of the drill bit [9]. Basically, it consists of a annular head with a circular brush, to be pierced with the drill bit (Fig. 4). The head is fitted with a funnel which directs the powder down into a vertical test-tube. This can be of transparent material, allowing to control the regular flow of the powder during drilling and to perform a first visual inspection. A narrow longitudinal cut, thin enough to prevent the powder to pass, makes possible to infiltrate the sample with the liquid chemicals used in some analyses (e.g. the phenolphthalein solution for the carbonation test).

One application of this device in the field of fire damage assessment concerns the detection of the pink-red discoloration taking place in heated concrete in the range 300-600°C [1, 9]. By properly processing a digital image of the powder filled test-tube, a profile of the colour alteration along the depth of the drilled hole can be obtained. Another implementation is the Differential Thermal Analysis (DTA), a test that involves the heating of a small sample of ground concrete in order to trace the transformations (and then the temperatures) that were not yet developed during the fire. A special nickel-chromium test-tube was devised to this purpose, with a series of small holes to allow monitoring the temperature of the powder sample during its heating to 1000°C, performing then several DTA tests in one take. The main limitation observed in these first two examples was the impracticality of controlling whether to include or not the coarse aggregate in the sample, leading to some dispersion in the results.

Going back to the original purpose of the Carbontest® device (namely to check the pH in the concrete cover), it has to be remarked that the main source of alkalinity in concrete pores is portlandite (calcium hydroxide), that decomposes gradually above 450°C and whose absence in the cement mortar is a marker of particular significance in fire safety of concrete structures. Although the de-hydroxylation of portlandite is a reversible process [11], the actual reinstatement of the pH conditions requires a sustained moist curing [12], which can be usually ruled out in elements protected from the rain.

In order to check the effectiveness of this method in post-fire damage assessment, the de-alkalinization depth was measured in the same concrete panel that was the object of the Hammer-Drill Pulse Velocity tests. By considering the scale factor between the length of the powder sample and the actual hole depth (about 2:1 for 10 mm bits), an almost uniform 26 mm depth was found (Fig. 4),

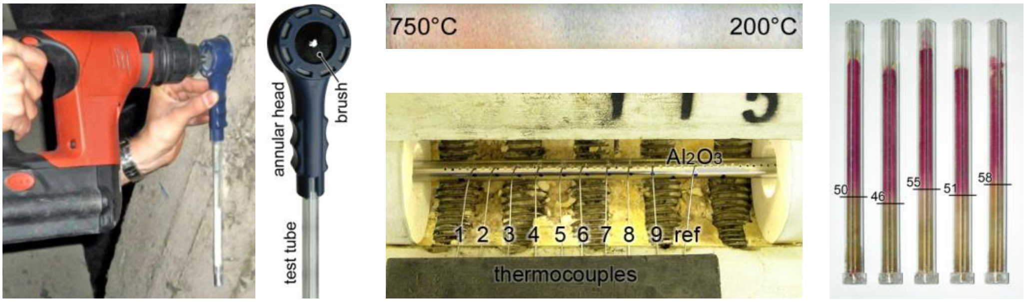

Figure 4. The Carbontest® tool for collecting the drilling powder, discoloration of a powder sample, setup for the multiple Differential Thermal Analysis, de-alkalinization depth in the panel of Fig. 3 (scale 2:1, in mm).

corresponding to a maximum temperature of 455°C (see the temperature profile in Fig. 3). This is in good agreement with the generally recognized point beyond which all the original portlandite is decomposed.

It is worth to note that this kind of analysis could not be performed on drilled cores, since the water used for cooling the diamond tool would reinstate the alkalinity in the pores before being able to perform the test. Moreover, the original carbonation depth in the structure at issue has to be preliminarily assessed, in order not to confuse the effects of normal ageing and exposure to fire.

2.3 Dynamic hardness of rebars

Contrary to concrete, whose deterioration due to fire is largely irreversible, steel rebars may recover a significant share of their initial strength during cooling. This feature strongly depends on the type of material (carbon vs stainless steel, quenched vs micro-alloyed bars, hot worked vs cold drawn bars) and a specific study is often required to determine the permanent damage undergone by the reinforcement [13].

An interesting alternative is provided by the dynamic hardness test (Leeb test, ASTM A956). Contrary to traditional static hardness tests (Brinell, Rockwell, Vickers), which require a bench-mounted tester and a precise optical measuring system, the Leeb method is well suited to on-site applications. In this test a body fitted with a hard spherical tip (Ø = 3 mm) impacts the sample surface under a spring force. The impact and rebound velocities are measured at approximately 1 mm from the impact point, through the electric potential induced in a coil by a permanent magnet mounted inside the impact body (Fig. 5). The ratio of these velocities, multiplied by 1000, is defined as the Leeb hardness number.

This scheme allows to develop compact handheld devices that can be easily positioned on the tested rebar. The method requires a flat and smooth surface, though with not very stringent limits (average roughness < 2 µm). Moreover, the sample should be firmly restrained, so to prevent any vibration which may reduce the impactor rebound. This may be not the case of rebars embedded in a damaged concrete cover, due to the possible debonding ensuing from different thermal strain or buckling.

In order to ascertain the sensitivity of this method to the decay of the residual yield strength, the following steel rebars have been tested:

- Quenched and Self-Tempered bars (QST - Ø = 10 and 16 mm). It is presently the most extensively used reinforcing steel in Europe.
- Micro-Alloyed bars (MA - Ø = 10 mm), incorporating alloying elements (Niobium and Vanadium).
- Cold-worked Stainless-Steel bars (austenitic AISI 304L steel - SS - Ø = 12 mm). Contrary to hot rolled bars of the same material, this steel is very susceptible to high temperature.
- Square-section, Carbon-Steel bars (CS - side = 12 and 20 mm). Currently produced in Italy in 1950-70, they exhibit a higher strength, but are more fire sensitive than smooth hot-rolled carbon-steel bars.

Normal 0.6 m samples (for tensile testing) and shorter pieces of rebars (for hardness testing) were

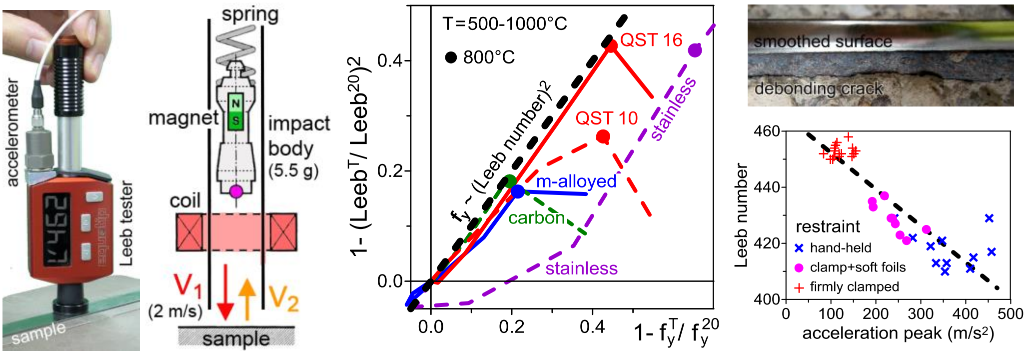

Figure 5. The Leeb tester fitted with the accelerometer for sample vibration compensation, functioning scheme of the instrument, correlation with the residual yielding strength and influence of the lack of restraint due to rebar debonding.

submitted to a series of thermal cycles (T_{max} = 500, 600, 700, 800 and 1000°C). The hardness tests were performed by clamping the samples in a heavy machine vice. The top side of each sample was milled and then polished with sandpaper. About 30 tests were performed on two samples for each steel-temperature combination, with fairly repeatable results (coefficient of variation < 5%).

The experimental evidence for all carbon steels up to 800°C (Fig. 5) show a very good correspondence between the decay of the residual yield strength and the reduction of the square of the Leeb number (namely the rebound kinetic energy). At higher temperatures an increasing hardness and a larger dispersion are observed, probably because of grain coarsening in the crystalline microstructure. Nonetheless, the cited correlation allows an easy assessment of the residual performance of carbon steel rebars in the temperature range of major interest, without requiring any prior knowledge about the type of steel. A totally different behaviour characterizes cold-drawn stainless-steel, possibly because of the lack of a true yield point and the remarkably increasing strain hardening exhibited by the damaged rebars (strength ratio $f_t / f_y > 2.5$), enhancing the role of tensile strength f_t compared to yield strength f_y.

Concerning on-site applications, it has been found that an ordinary angle grinder fitted with flap-discs is a viable solution to flatten the rebar side, provided that work piece is not overheated. The final smoothing is performed by using a mini-drill and high grit sandpaper discs. Regarding the possible vibration of the tested bar due to debonding, a linear relation has been found between the peak acceleration of the tester body and the reduction of the Leeb number relative to the case of an effective restraint. If neglected, this effect may lead to an underestimate of the residual strength up to 10-15%.

3 COMBINED INTERPRETATION OF RESULTS

Despite of the wide assortment of inspection tools that may be conveniently used for post-fire assessment, a complete characterization of both the maximum damage at the surface and the heat penetration in the core of a concrete member generally requires the combined implementation of several methods. Limiting the discussion to techniques not requiring too demanding on-site operations nor laboratory analyses, the following brief summary can be drawn (Fig. 6), based on direct experience of the author [1, 5] and literature review [2-3, 6]:

- <u>Rebound hammer</u>. It detects the average response of the cover at a notional depth of about 15 mm, provided that the experienced temperature exceeds 500°C.
- <u>Cut And Pull-Out</u> (CAPO) test. It exhibits an excellent sensitivity to the strength decay in the whole range from pristine to severely damaged. The information pertains to just a few millimeters depth.
- <u>Colorimetry</u>. The pink discoloration occurring at 300-600°C can be detected at any depth, once a proper sample has been taken from the structure. In the author experience the 450°C isotherm can be detected with digital image processing without a specific calibration for the concrete at issue.

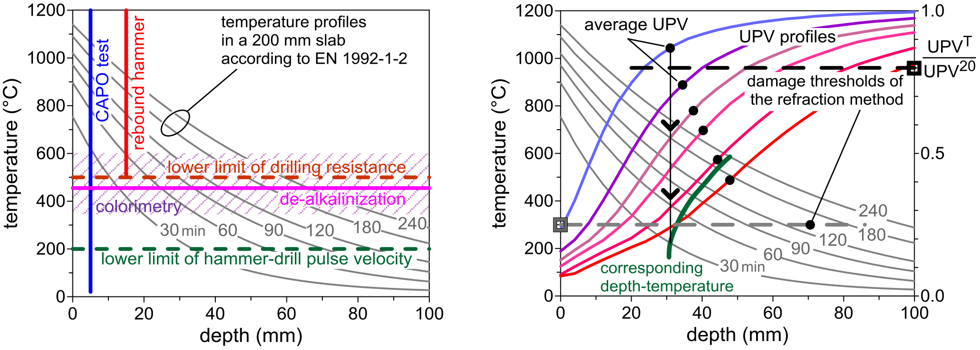

Figure 6. Sensitivity range of some common inspection techniques and connection between the temperature profiles and the expected pulse velocity values sensed by the ultrasonic techniques.

- De-alkalinization depth. A much sharper front than pink discoloration is detected by using a pH indicator on a dry powder sample. It corresponds to a maximum temperature of about 455°C.
- Drilling resistance. In principle, the drilling work and time can be measured at any depth. The onset of the thermal decay is generally observed at about 500°C.
- Drilling pulse velocity. This new technique is definitely more sensitive than its predecessor. One limitation of the present version is that a double-sided access to the inspected member is required.
- Average Ultrasonic Pulse Velocity via direct transmission. It provides the total transit time of ultrasonic pulses through the member thickness (integral of the slowness, i.e. 1 / pulse velocity). Due to the remarkable heterogeneity of crossed layers, the interpretation requires some assumptions on the temperature profile and the velocity decay [1]. This is functional to work out a velocity profile (Fig. 6) and, finally, to validate the measured value of the average pulse velocity (1 / average slowness).
- Ultrasonic Pulse Refraction via indirect transmission. The pulse velocity profile can be identified by applying both ultrasonic probes on the surface exposed to fire, according to the refraction technique. The migration algorithms commonly used in geophysics may be implemented to reveal the velocity profile. As an alternative, some correlation diagrams have been produced [1, 7] to detect the thickness of the significantly damaged layer (UPV < 80% UPV^{20}, T > 300°C).

As concerns the temperature profiles which develop in concrete members exposed to fire, they are the final result of heat conduction under the thermal input coming from the burning compartment. In fully developed room-fires this latter depends mainly on the specific fire load (q_t , referred to the total surface area of the compartment), the opening factor (O, governing the rate of heat release in ventilation controlled fires) and the thermal properties of the enclosure surface (which rule the heat absorbed and later released by the lining materials).

By considering the parametric temperature-time curves indicated by Eurocode 1, the envelope profiles of the maximum experienced temperature have been worked out (Fig. 7), including the further

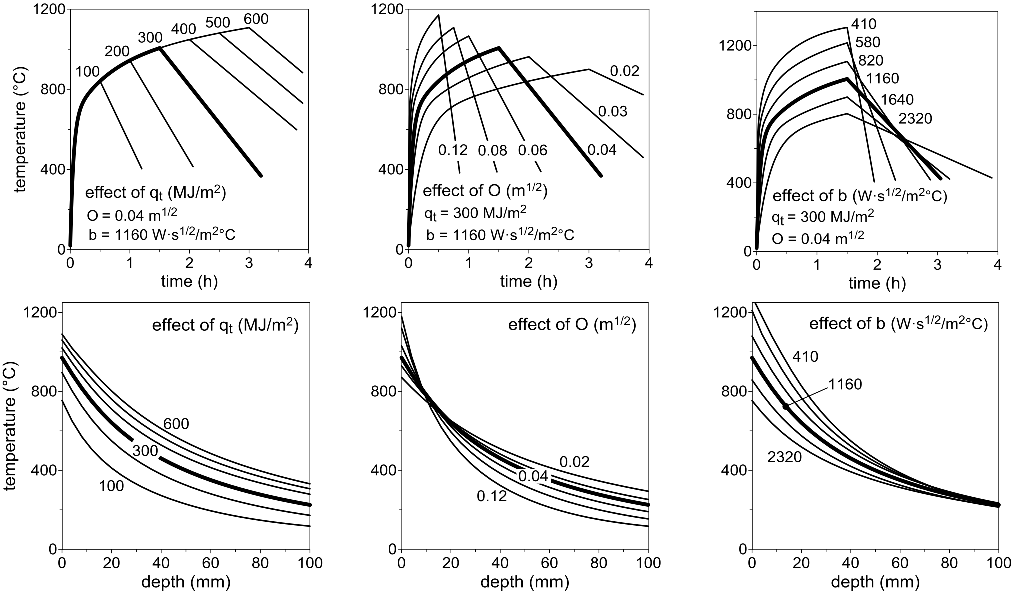

Figure 7. Influence of specific fire load q_t, opening factor O and square root of thermal inertia b on the parametric temperature-time curve and on the corresponding maximum temperature profiles in a 200 mm thick concrete slab.

heat propagation occurring during the decay stage of the fire. It transpires that all the cited techniques are expected to exhibit a good response to a variation of the fire load, thanks to the regular evolution of the temperature profiles. If one considers also the fuel loss due to external flaming, this is often the most uncertain parameter in the identification of a fire scenario. On the other hand, a change of the opening factor may lead to wrong conclusions if one relies on just a surface inspection, since small vents translate into relatively colder but - on the whole - more severe fires. This aspect can be hardly revealed by the techniques detecting a temperature threshold of 450-600°C (e.g. colorimetry and de-alkalinization). Finally, the presence of insulating and lightweight lining materials (low values of b) tends to boost the surface damage compared to the average impact on the cross section, though also in this case a combination of assessment techniques pertaining to different depths should allow to tackle this aspect.

4 IDENTIFICATION OF THE FIRE SCENARIO IN A FURNITURE SHOP

One example of merging the results ensuing from several assessment techniques, through a parametric analysis of the fire scenario, is provided by the case study of the total burnout of a furniture shop. The building has a regular open plan (12.5 x 40 m) and comprises 3 storeys above ground, characterized by different soffit heights (3.8, 3.3, and 3.0 m from ground to roof) and different opening factors (O = 0.18, 0.09 and 0.06 $m^{1/2}$ respectively). The bearing structure is a cast-in-place concrete frame, constructed in many batches of rather variable quality, according to the normal practice in the '60s. Based on the fire brigades report and photographic evidence (Fig. 8), the fire started at ground floor and propagated through an open stair directly to the second floor, and later to the first floor. The burning stage at each floor lasted between 30 and 60 minutes.

The complex sequence of the events, the vertical draught through the stair and the lack of data on the distribution of the fire load dissuaded from modelling the fire scenario of the entire building. Nonetheless, the results of the ND tests performed all over the structure indicated that the N-E edge of each storey was the most severely affected part of the building. Then, these portions were considered as separate virtual compartments, to be analysed via a numerical zone model (Ozone 2.2.5), including the realistic description of the opening factor and of the thermal properties of the materials lining the compartments. Conversely, the fire load was kept as a free parameter, allowing to adjust the fire severity until the indications provided by the on-site inspections were met.

Limiting the discussion to the possible fire scenario developed at the first floor, a series of time-temperature curves have been produced (Fig. 8), under common assumptions concerning the evolution in time of the Rate of Heat Release (t-squared growth with medium rate, max RHR = 250 kW/m^2, decay starts at 30% residual fire load). Due to the relatively large opening factor, both the numerical analyses and the EN 1991-1-2 parametric fire would indicate a remarkably fast cooling in the decay stage. It is worth to note that the Ozone software doesn't allow for the inverse heat flux returned by the enclosure walls in the end of the fire. This issue has been addressed by Feasey and Buchanan, who proposed some refinements to the reference parameters and the time scaling factors of the parametric fire [14].

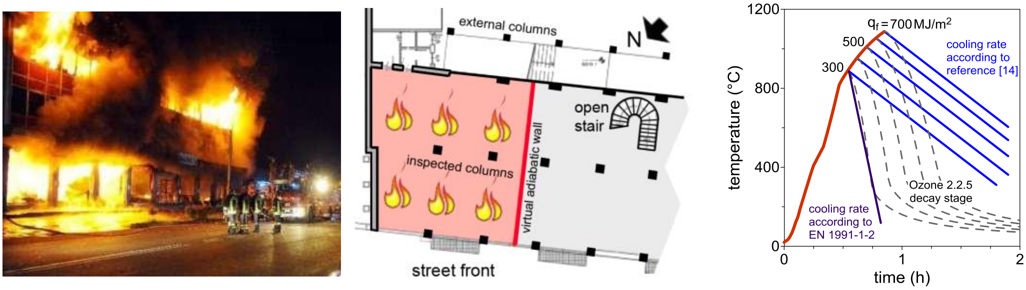

Figure 8 - View of the burning stage at the ground and second floor of the furniture shop, sub-compartment considered in the analysis of the fire scenario at the first floor and time-temperature curves obtained via the zone-model.

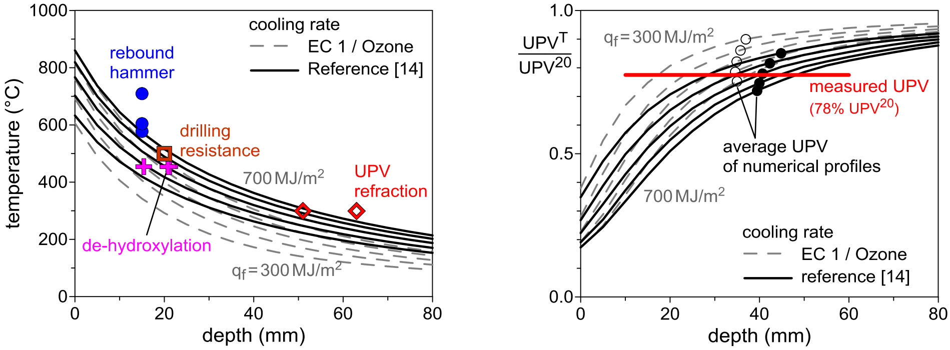

Figure 9 - Comparison between the results of the on-site inspection techniques and the temperature profiles produced by the time-temperature curves of Fig. 8 along the cross-section axis of a 400x400 mm concrete column; corresponding Ultrasonic Pulse Velocity profiles and comparison with the average through transmission velocity.

As concerns the onsite inspection of the damaged elements, it has been decided to focus the attention on the top part of the central columns, due to their representative location and the minor influence of rebars and cracks compared to the beams. The columns (400x400 mm, loaded at about 10% of their mean capacity) were lined with a 10 mm layer of plaster, which partly fell off during the fire. Being the progress of this occurrence unknown, a permanent plaster layer of half thickness has been considered in the thermal analyses. A summary of the ND results and the potential temperature and Ultrasonic Pulse Velocity profiles are reported in Fig. 9 (the latter are based on the decay plot presented in [1, 7]).

It has to be pointed out that the interpretation of many ND results relies on the comparison between the material responses before and after damage. In real situations just the average original quality of concrete can be assessed, by checking like elements not exposed to fire (in this case the columns located outdoor and in the basement). Due to the poor quality control during construction of the structure at issue, the apparent effects of fire in a specific member may be enhanced (or offset) by the initially lower (or higher) grade of concrete compared to the average. This is a further reason for merging the results from several techniques, preferably taken from different members of the same compartment. In principle, the depth of de-hydroxylation (related to a specific chemical transformation) and the drilling resistance (based on a comparison between deep and shallow layers crossed by the same hole) should be less influenced by this source of uncertainty.

The final outcome is that the highest fire load in the considered range (q_f = 600-700 MJ/m^2 per unit floor area) and the slower decay rate [14] seem to fit better the experimental results. A larger dispersion is exhibited by the surface hardness, whereas the drilling result required averaging more tests (5 in this case) for detecting the onset of the drilling work decay. The ultrasonic refraction method entailed a careful examination of the received signals, due to the dramatic attenuation of pulses in the damaged cover. The direct transmission of the ultrasonic pulses proved to be far more viable, although the interpretation would have not been possible without the aid of a fire scenario model and of the corresponding temperature profiles. This latter technique involves the entire thickness of the inspected member and is less influenced by the further weakening which may affect the external layers in the months following the fire (due to moisture absorption from the environment).This is probably the reason why a slightly lower fire load (q_f = 500 MJ/m^2) is more consistent with this latter results.

5 CONCLUDING REMARKS

In this paper new inspection tools and a procedure for the coordinated interpretation of the results have been presented, aimed at devising a practical and sound approach to post-fire damage assessment of concrete structures. The main conclusions that can be drawn from this work are listed in the following.

- Monitoring the velocity of the strong pulses generated by a hammer-drill combines the viability of the drilling method with a definitely higher sensitivity to mild damage levels. Some studies are in progress to develop a more affordable tool and a more flexible test configuration.
- Tracing the alkalinity of a sorted sample of drilling powder is a very quick method (about 1 minute per test) for detecting the depth of the 450°C isotherm. Further investigations are needed to check the influence of concrete composition, ageing and ambient moisture.
- The standard dynamic hardness test is a practical solution to assess the residual yield strength of rebars. A quite general correlation has been found for ordinary carbon steels up to 800°C. For other materials (work hardened and stainless steels) the method can be used to extend the results of destructive tests. The possible bar debonding may translate into to a sizeable strength underestimate.
- The coordinated comparison of on-site inspection results against the temperature profiles produced by a parametric analysis of the fire scenario is an effective way a) to merge indications pertaining to different ranges of depth and temperature and b) to form a more reliable picture of the residual condition of the structure. Since in the end a fire scenario of reasonable severity is validated, the significance of the results may be extended well beyond the inspected members.

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