Nondestructive Evaluation of Fire-Damaged Reinforced Concrete

by Jacob Borgerson and Joshua White

Fig. 1: A reinforced cast-in-place concrete structure that was damaged due to a fire event

When reinforced concrete is exposed to fire, both the concrete and reinforcement may be altered, which can result in structural and material damage. Figure 1 shows a photograph of a cast-in-place concrete structure that was damaged due to a fire event.

The repair strategy for fire-damaged structures depends on the severity of damage. When characterizing severity, it is important that an evaluation considers both the extent of damage (i.e., identifying portions of the structure affected) as well as the depth of damage (i.e., how much of a particular beam, column, or slab section is damaged). While both can be characterized by laboratory testing of extracted samples (i.e., concrete cores and steel reinforcing), the scale of material sampling can often be very large, expensive, and time consuming. The nondestructive evaluation (NDE) methods discussed in this article can be used to better understand the extent of damage more efficiently than laboratory testing alone. Once the extent of damage is characterized by NDE, targeted laboratory testing can then be used to determine the depth of damage and approximate exposure temperatures in order to develop repair strategies.

FIRE EXPOSURE FAILURE MECHANISMS AND DISTRESS CONDITIONS

When reinforced concrete is subjected to fire exposure, both the concrete and reinforcement can be altered and exhibit distress conditions.[1] As the surface temperature of a concrete element increases, surface crazing may occur, followed by cracking and spalling as heat transfers to the interior of the concrete. At relatively high temperatures, there may be a loss of concrete compressive strength due to irreversible microcracking and volume change of the matrix. Depending on the size and duration of the fire, some heat may transfer to the steel reinforcement. At elevated temperatures, there may be a reduction of the steel yield strength, particularly if spalling occurs and exposes the reinforcement.

Assuming there is fuel and ventilation available, compartment fires (e.g., room fires) can fully develop and achieve flashover. Flashover can be visually characterized by flames extending from a doorway/window and involving the available fuel in the compartment. When flashover occurs, the upper gas layer will achieve temperatures exceeding 1110°F (600°C).[2] As such, if flames extend out of the space of the compartment during the fire, it is likely that portions of the concrete structure would be exposed to gas temperatures exceeding 1110°F (600°C), particularly the elements toward the ceiling space (i.e., slab, joists, beams).

When concrete is exposed to heat (i.e., fire), cracking, spalling, and discoloration can occur. An understanding of these mechanisms can provide insight into the extent and nature of the fire damage. In addition, knowledge of the fire damage failure mechanisms and distress conditions helps provide context for an evaluation methodology.

Cracking related to fire damage is typically a result of restraint from thermal expansion due to temperature differentials between the exterior surfaces of a concrete element and the cooler interior concrete, often seen at the corners of concrete elements. Depending on the type of aggregate present, cracking can also be attributed to thermal expansion of aggregates which can lead to internal microcracking, popouts, and/or crazing. Figure 2 shows an example of cracking that occurred in a concrete joist due to fire exposure.


Fig. 2: Cracking along the length of a reinforced concrete joist due to fire exposure

Spalling is the surface flaking or disengagement of a fragment of concrete and can occur in the temperature range between approximately 300°F to 570°F (150°C to 300°C).[3] Figure 3 shows an example of spalling that occurred on a concrete column due to fire exposure. While opinions differ on the dominant mechanism that causes concrete spalling, it is generally believed to be caused by a combination of vapor pore pressure and thermal stresses.[3,4] Spalling induced by vapor pore pressure occurs when the free water in the concrete vaporizes and expands, causing the internal pressure to exceed the tensile strength of the concrete. Spalling induced by thermal stress is the result of a thermal gradient that induces near-surface compressive stress (due to restrained thermal expansion), creating a fracture plane between the heated surface and the cooler interior region.


Fig. 3: Spalling that occurred on a concrete column due to fire exposure

The color of concrete aggregates and paste may change during heating, depending on the concrete constituents. Color changes, if observed, can provide an indication of the maximum exposure temperature. At approximately 480°F to 570°F (250°C to 300°C), there is often a color change to pink/red; at approximately 930°F to 1110°F (500°C to 600°C) there can be a color change to purple/grey.[5] The intensity of the color change is mostly dependent on aggregate type (i.e., presence of certain minerals). These color changes can provide a visual indication of the depths of general heat exposure within a concrete member and can thus provide an indication of the approximate temperatures of the underlying steel reinforcement.


Fig. 4: Spalling of concrete box beam and exposed prestressed strand due to fire event

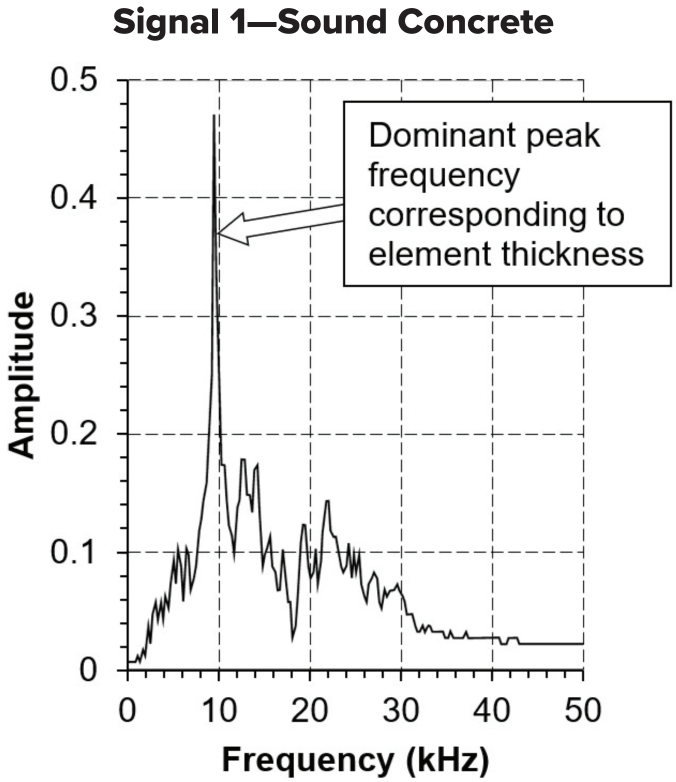
The reinforcing steel within concrete elements may be exposed during a fire event (Fig. 4) and, as a result, may also be affected by elevated temperatures. Strength reduction in reinforcing steel may occur while the steel is at high temperatures; however, the yield strength may recover after cooling. For hot-rolled steel reinforcing bars, the yield strength is typically recovered for temperatures less than approximately 1110°F (600°C).[1,6,7] As such, for exposure temperatures greater than 1110°F (600°C), yield strength and/or ductility of the steel reinforcement may be reduced.

NONDESTRUCTIVE EVALUATION OF REINFORCED CONCRETE STRUCTURES EXPOSED TO FIRE DAMAGE

Visual assessment is one of the simplest methods for nondestructively evaluating reinforced concrete structures for fire damage. As described earlier, evidence of fire damage typically consists of surface defects such as cracking, spalling, and concrete discoloration. While visual assessment is effective, it does not provide an evaluation of the concrete beyond what is visible (e.g., beyond the exterior surface). Consequently, visual assessment should be performed in conjunction with other nondestructive evaluation techniques, such as acoustic sounding, techniques utilizing stress waves (e.g., impact echo, ultrasonic pulse velocity, ultrasonic tomography), and ground penetrating radar.

Acoustic sounding can be used to determine if concrete has delaminated. The method involves applying an impact and listening (i.e., via the unaided human ear) for dull or hollow sounds. For vertical and overhead concrete elements, an impactor (typically a hammer) is used to tap the concrete surface. For locating delaminations on top of reinforced concrete slabs, the chain drag method is usually implemented because larger areas can be evaluated more efficiently. While acoustic sounding is a straightforward and relatively simple technique, experience is required in order to differentiate between dull/hollow sounds that are consistent with delamination and other sounds that appear dull or hollow but are due to the concrete element's geometry. For example, acoustic sounding at the bottom of a narrow double tee beam stem may sound more or less hollow than sounding at the top of the stem. This acoustic difference is due to the support condition of the concrete element and should not be interpreted as delamination.

Impact echo (IE) can be an effective method for detecting micro-cracking and delaminations within concrete elements exposed to fire. The IE method involves introducing mechanical energy, in the form of a brief impact, to the concrete test element (e.g., slab, beam, or joist). An impactor is used to generate a stress wave through the concrete element. Stress waves reflected from internal discontinuities or member boundaries are measured using a signal displacement transducer positioned near the impact. As the transmitted energy travels through the material, any changes in acoustic impedance within the material reflects a portion of the energy back to the surface. With knowledge of the propagation velocity (i.e., wave speed) of the material and the frequency spectrum of the reflected waveform, the depth to discontinuities (i.e., internal flaws) or the member boundary can be determined. Figure 5 provides a comparison of representative IE results in undamaged and damaged areas. For example, Signal 1 provides a typical frequency domain for sound concrete with a dominant peak frequency corresponding to the thickness of the element, while Signal 2 shows a frequency domain with multiple frequency peaks which is likely caused by cracking and/or a spall in the concrete. In Signal 2, the dominant



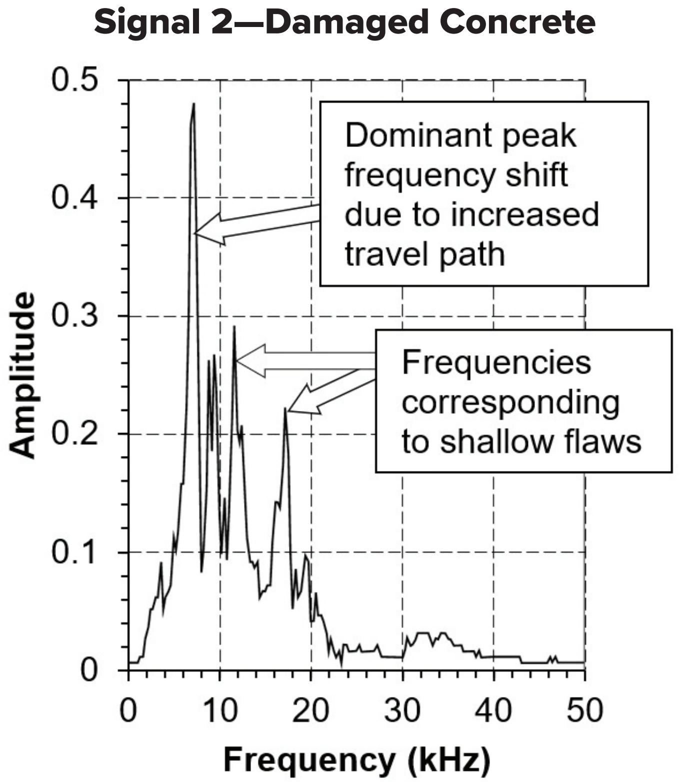


Fig. 5: Comparison of representative IE results in damaged and undamaged areas

frequency peak has shifted compared to the sound concrete, which is characteristic of damaged concrete members due to the increased travel time of the stress waves.

Shear wave ultrasonic tomography (UST) is a reflective ultrasonic test method capable of generating 2D and 3D tomographic images of internal conditions within concrete elements. The method can be used to detect internal flaws such as spalls and cracking. UST testing devices consist of a sensor array incorporating dry point contact piezoelectric transducers. Each transducer emits ultrasonic shear waves (S-waves) and receives waves reflected from relative changes in acoustic impedance (e.g., material boundaries or flaws). Scans that are collected at sound concrete (free of sizable voids, cracks, or spalls) are characterized by a strong signal reflection that corresponds to the back wall, or full-thickness of the tested element. Areas where internal flaws are present are characterized by 1) the absence of a back-wall reflection due to the presence of internal reflectors, near-surface degradation, or both; and/or 2) signal reflections corresponding to the depth of the flaw. Figure 6 provides a comparison of representative UST results in undamaged and damaged areas. For example, Signal 1 provides a typical frequency domain for sound concrete with a dominant frequency peak corresponding to the thickness of the element, while Signal 2 shows a frequency domain with multiple frequency peaks which is likely caused by cracking and/or a spall in the concrete. In Signal 2, the dominant frequency peak has shifted compared to the sound concrete, which is characteristic of damaged concrete members due to the increased travel time of the stress waves.

The ultrasonic pulse velocity (UPV) method involves introducing pulsed longitudinal stress waves (P-waves) at the surface of a test element and then measuring the waveform at an opposing face. Stress waves are transmitted and received using piezoelectric transducers that are acoustically coupled to the test surfaces. Transit time and signal amplitude of a transmitted pulse are measured, and detected changes in arrival time, amplitude, and characteristics of the propagated waves can indicate corresponding differences in the internal condition of the element. For the testing of concrete, sound regions exhibit little variation in propagation velocity and exhibit strong signal transmittance, with nominal signal attenuation normally associated with varying path lengths through the member. The presence of internal flaws or areas of deterioration typically adversely affect the velocity and amplitude during stress wave propagation. Poor surface conditions, such as delaminations, laitance, or unsound surfaces, can also result in significant signal attenuation during testing. Figure 7 provides an example showing the effective wave velocity along the height of two concrete columns that were exposed to a fire event.

Ground penetrating radar (GPR) is a geophysical method used for the assessment of structural elements and geo-

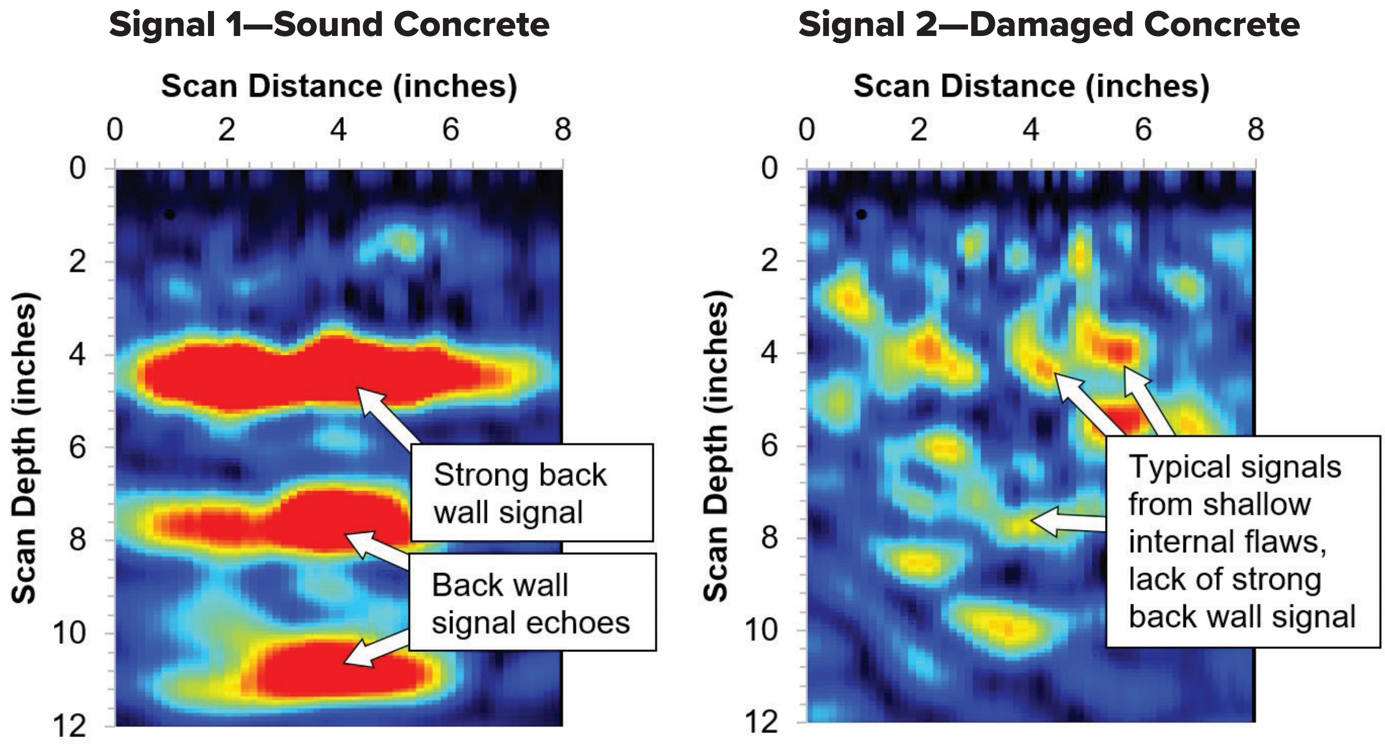


Fig. 6: Comparison of representative UST results in damaged and undamaged areas

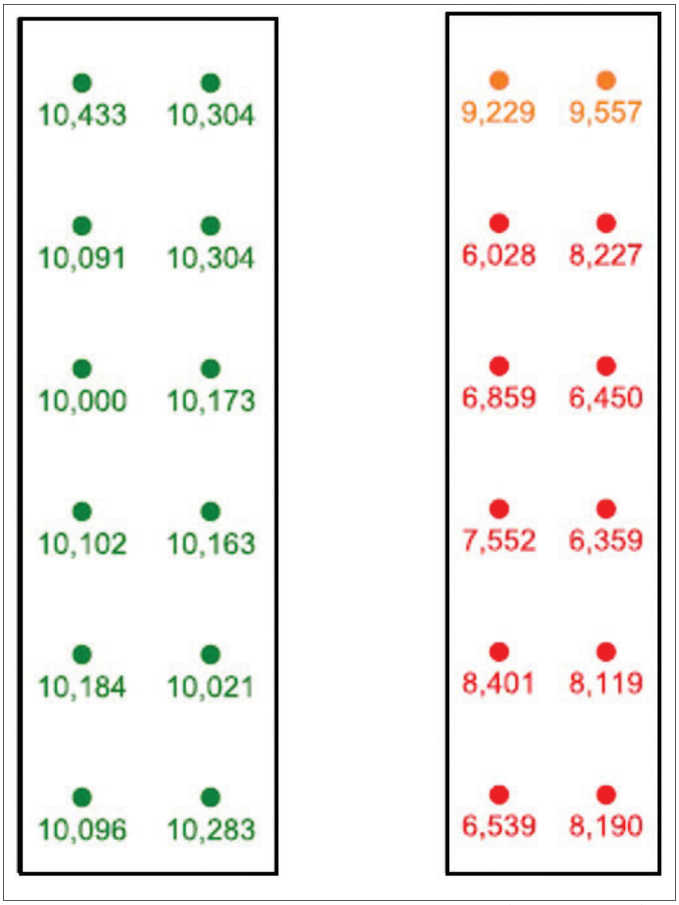


Fig. 7: Comparison of representative UPV material velocities (feet per second) for an undamaged concrete column (left image) and a damaged concrete column (right image)

logical materials. GPR testing of concrete allows for the detection and location of embedded elements (e.g., steel reinforcement, prestressing/post-tensioning strand, metal and plastic conduit), internal voids (such as poor consolidation), and assessment of member thickness and element geometry. The test method involves the use of a dipole radar antenna which transmits electromagnetic wave pulses along discrete scans at the surface of the structural element. The electromagnetic waves propagate through the material and reflect at material interfaces characterized by a change in dielectric properties. The reflected waves are collected by the antenna and are amplified, filtered, and displayed for subsequent interpretation. Post-processing software integrating signal filtering and visualization options allows for subsequent analysis of collected GPR scans. When the depth of damage (i.e., estimation of temperature as a function of depth) is known, knowledge of the reinforcement placement using GPR helps determine if damage to the reinforcing steel is expected in areas where the concrete cover remains intact.

SUPPLEMENTING NDE FINDINGS WITH LABORATORY TESTING

Once the extent of damage is characterized by NDE (e.g., one might subdivide the structure into areas of "poor", "fair/questionable", or "good" condition), the depth and nature of the fire damage can be evaluated by extracting samples for laboratory testing.

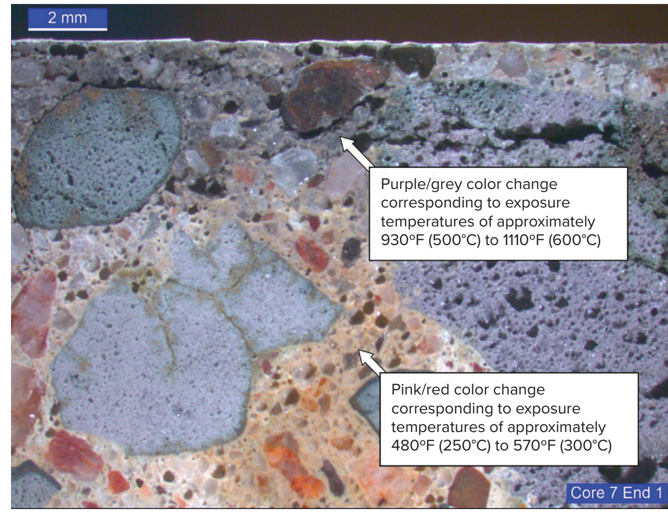


Fig. 8: Lapped cross-sectional surface of concrete core showing color change due to variation in exposure temperatures

Concrete cores are typically extracted from the structure and examined microscopically using petrographic examination. Petrographic examination is often used to assess the quality of hardened concrete and can help determine the effects of exposure to elevated temperatures on the concrete. Alterations in the aggregate and paste are associated with exposure to a range of elevated temperatures, but these alterations are also dependent on the duration of the exposure, features of the concrete, and the quenching operations used to extinguish the fire. Figure 8 provides a lapped cross-sectional surface of a concrete core showing color change due to fire exposure.

If the majority of the defective concrete is near-surface damage, it should not have an appreciable impact on the concrete compressive strength of the tested cores. Conversely, cores can be extracted and tested to directly measure potential reduction in concrete compressive strength that may be attributable to heat exposure during the event.

If the petrographic examination indicates that the concrete at the depth of the reinforcing steel (e.g., as determined by GPR) did not exceed 1110°F (600°C), no damage to the reinforcing steel is expected in areas where the concrete cover remains intact. In areas where steel reinforcement is exposed (presumably during the fire event), it may have achieved surface temperatures exceeding 1110°F (600°C) and some strength reduction in the reinforcement may have occurred. As such, sections of the steel reinforcement may be removed at select locations to evaluate its mechanical properties (i.e., yield and ultimate tensile strength).

SUMMARY

Assessment of a reinforced concrete structure exposed to fire damage is often necessary to determine the scope of repairs. While there are many approaches to evaluating fire damage of reinforced concrete, NDE can provide an effective approach for surveying the extent of potential fire damage and can be valuable in a structural and materials evaluation. When considering NDE as part of a fire damage assessment, it is typically beneficial to utilize a multi-method approach. The findings from NDE should be supplemented with laboratory testing to determine the depth of damage and, if needed, quantify strength reduction in the concrete and/or steel reinforcement.

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