An Innovative Approach Assuring the Successful Repair of Fire-Damaged Reinforced Concrete Structures

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Background

When considering fire as a topic for discussion, we need to initially discuss its components - namely oxygen, fuel & heat – the triad of fire. Eliminating one part of the triad will effectively extinguish the fire event and is one of the fundamental characteristics of successful firefighting. When reviewing the types of fires that reinforced concrete structures are exposed to can range across the spectrum following the nomenclature associated with Fire Extinguisher products[1] including:

Type A – Cellulose-Based Fuel Sources

Type B – Hydrocarbons

Type C – Electrical Fires

Type D – Reactive Metals

When speaking of concrete, we're really addressing the most widely used and versatile building construction product on the face of the earth. Essentially, a castable stone product incorporating sand, cement, coarse aggregate, water and chemical/mineral admixtures, the resulting hardened mixture (i.e., concrete) is incombustible and performs extremely well in a fire. Physical characteristics of hardened concrete include good compressive strengths, a highly alkaline internal environment but relatively weak tensile strength properties. As such, since the late 19th Century, reinforcing steel bars have been incorporated into concrete structural members to form a composite section. When adequately designed, this composite is capable of carrying not only compressive loadings, but also flexural (i.e., tensile) loads via the incorporation of strategically placed steel within the concrete mass. Additionally, concrete's highly alkaline environment effectively "passifies" embedded reinforcing steel systems providing protection from embedded metal corrosion, and environmental protection through a protective concrete cover thickness.

Concrete Materials

As a man-made construction building product, concrete has some unique physical properties that serve it well during high temperature exposures such as in the case of fire. Thinking about concrete, we really need to understand that concrete is effectively a "hard sponge" that is made up of a series of pores and capillaries that form during the hardening process[2]. Excess moisture fills these pores and capillaries as there is always excess moisture added to fresh concrete mixtures to assist in its place-ability, beyond the water required for hydration (i.e., the chemical reaction involved with the hardening process). As a material, concrete is "hydroscopic" meaning that it freely absorbs and gives up water when exposed to the environmental conditions such rain and high heat. During a fire event, depending on its fuel source and duration, moisture within the concrete will initially travel from within the concrete mass to the surface in an attempt to cool the surface. After a period of time, as all concrete behaves differently based on its design, mixture constituents and subsequent to the depletion of near surface moisture, concrete undergoes "structural changes" in the cement paste matrix (essentially the glue that holds the concrete together) and bound fine & coarse aggregate. The cement paste "desiccates" forming a network of micro-cracks depending on internal temperature gradients with the chemical composition degrading to a point where water is liberated from the hydrate. This liberation weakens the aggregate to paste bond thereby reducing the concrete material strength. In addition, many fine & coarse aggregate types undergo a process of expansion within the concrete mass.

Forensic evidence available from the site of a fire typically involves telltale indicators in lieu of thermocouple information that would be available from a laboratory during fire endurance investigations. Generally, concretes made with siliceous or limestone aggregate exhibit color changes in association with high temperature exposures. This color change is thought to be associated with and dependent on the presence of certain iron compounds within concrete, so coloring will vary from concrete to concrete. The coloring however is permanent with generalized temperature sequencing for non-refractory concrete shown below:

Figure 1 – *Heat Exchanger Foundations exposed to a long duration Hydrocarbon-fueled fire event creating concrete delaminations (i.e., partially detached near surface internal separations) and spalls (i.e., detached delaminations), exposing embedded reinforcing steel and anchor bolts.*

Exposure Temperature	Concrete Color	Strength Reduction
32 to 570°F (0 to 300°C)	Unchanged	Unchanged
570 to 1,100°F (300 to 595°C)	Pink or Red	0 to 55%
1,100 to 1,650°F (595 to 900°C)	Gray	55 to 85%
1,650 to 2,200°F (900 to 1,205°C)	Buff	85 to 100%
Greater than 2,200°F (> 1,205°C)	Yellow	Complete decomposition of the cement paste where Calcium Hydroxide converts to Calcium Carbonate

Using the above guideline, the residual strength for non-refractory concrete can be approximately judged; generally, concrete whose color has changed to pink or beyond is suspect, and concrete past the gray stage is probably friable and porous.

Concrete Behavior During a Fire

Considering the behavior of concrete as a material, we should note that fire introduces high temperature gradients and as a result, the hot surface layers tend to separate and spall from the cooler interior of the body mass. Crack formation begins to propagate at joints, in poorly consolidated parts of the concrete, or in planes of reinforcing bars. Once reinforcement has become exposed, it conducts heat and accelerates the action from high temperature exposures. For practical purposes, about 1,100 °F (595 °C) can be considered as a limiting temperature for structural integrity of concrete members constructed of non-refractory concrete. This limit pertains to the surface temperature of the concrete member element itself and not the temperature of the flame or of the gases.[3]

When initially exposed to high temperatures, such as in the case of a fire as stated earlier, concrete cools it's contact surfaces with free-moisture and chemically-released moisture from interior regions of the concrete mass. Concrete, with its network of pores, small conduits or capillaries, allow the passage of water from interior to exterior regions. However, as moisture moves within the concrete, small amounts of soluble salts are in solution which deposit within the pores of the concrete as the water evaporates during a fire event. As the salt deposits fill-in voided areas, the concrete pores become blocked and do not allow further transfer of water to cool high temperature contact surfaces. Therefore, the water accumulates behind this barrier and is phase changed from a liquid to a gas. This gas or steam expands in volume and pressurizes the concrete within unblocked pores. The steam pressure ultimately exceeds the tensile capacity of the concrete creating a surface spall (Refer to Figure No. 1 above). This mechanism is why poorly detailed thin "feather-edged patch" repairs to fire damaged concrete members do not work as the patch will fail explosively during a subsequent fire event. Steam builds along the repair material/concrete bonding interface and "hurls" the patch along with a thin layer of parent concrete that has failed in tension.

The influence of concrete moisture content on strength is apparent where excessive moisture at the time of the fire is the primary cause of spalling. In general, moisture content of the concrete is the most important factor determining its' structural behavior at higher temperatures (Refer to Figure No. 2 below). In large or relatively thick concrete members, moisture movement is extremely slow so that the effects of a high temperature event, while loss of water is prevented, may be more serious than in thin members. Fire suppression efforts, although a priority at the time of the fire, typically does more damage to concrete than allowing the concrete to cool slowly. Specifically, the application of water to hot concrete surfaces during firefighting activities is like "quenching" the concrete. This practice causes a large reduction in strength because severe temperature gradients are set-up in the affected concrete member.[3]

Figure 2 – *Spalled concrete piece that jettisoned off of a concrete Column member which was only 3 days-old at the time of the fire event due to "green concrete conditions". Significant moisture in near surface regions phase-changed the pore moisture from liquid water to steam. The steam formation pressurized the denser concrete surface creating internal separations approximately ¾" (19mm) in thickness, roughly the size of the coarse aggregate in the concrete mix.*

Concrete Reinforcing Systems Subjected to Fire

As mentioned above, structural reinforced concrete members incorporate steel reinforcing systems within the concrete mass to form composite members that can accommodate both compressive and tensile stresses under load. Conventional reinforcement in the form of steel bars and prestressed reinforcement, involving highly tensioned wire, strands or stress bars, are generally unaffected by a fire as long as the reinforcing systems aren't exposed during the event. The protective concrete cover typically "sacrifices" itself during a fire. Unless a high temperature accelerant (i.e., hydrocarbon) is the fuel source or the structural member was subjected to a long duration high temperature exposure, embedded reinforcing steel systems are often found intact and can be incorporated into the restoration program for repair of the structure. However, should these systems become exposed during a fire, thoughtful consideration and testing will be necessary before determining the acceptance or rejection (i.e., augmentation or removal & replacement) of the existing fire affected reinforcement.

When steel is subjected to high temperatures, it inherently wants to expand based on its thermodynamic properties. When exposed, conventional reinforcing steel bars expand and break the bond along the bar/concrete interface, compromising the composite section that depends on this engagement. Prestress reinforcing systems actually "relax" due to this growth and the all-important compressive forces generated as part of the system that allows for thinner more compact structural sections now become structurally suspect based on this relaxation[4]. As stated earlier regarding concrete materials, firefighting efforts in the form of streaming water can actually quench high temperature exposed steel components changing the metallurgical properties of the systems, making them less ductile and reducing their overall strength.

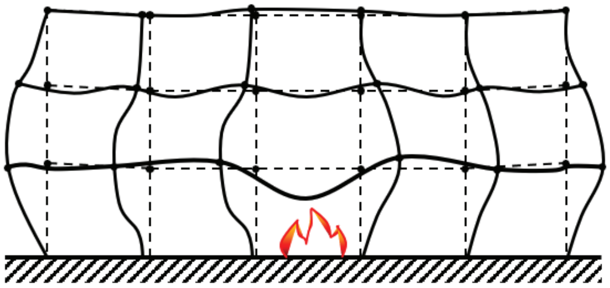

Figure 3 – *Global Structural Effects associated with a fire event on a Moment resisting Frame Structure*

Global Effect of a Localized Fire on a Reinforced Concrete Structure

The familiar statement of "can't see the forest through the trees" resonates when trying to assess the true extent of fire damage on a structure. Reinforced concrete frame structures can be significantly affected in regions some distance away from the location of a fire by its interconnected structural behavior of adjacent components directly influenced by the event (Refer to Figure No. 3 below). A case in point might be a continuous floor slab area that distorts several bays areas away from the fire but due to expansion and/or contraction created during the fire, significant structural damage and built-up stresses form within these structural members which must be relieved prior to repair. Repairs may have to be made to columns, beams, floor slabs, anchor bolts, etc. that may not have been visually apparent during initial investigative efforts that focused on localized fire damaged members and was only evident once the structure was viewed in its totality.

Myths of Reinforced Concrete Fire Damage

- Concrete Burns – Concrete consists of non-combustible mixture constituents and therefore as a hardened product, concrete won't burn.
- Black "Sooty" Concrete Needs to be Removed and Replaced – Depending on the location to the pyrogenic epicenter (i.e., focus of the fire), concrete stained by the combustion products from the fire's fuel source, doesn't always mean that the stained regions are affected structurally from the event. In fact most investigations will determine that these areas are actually away from the flame impingement and once cleaned of the combustion residue are actually fit for service. (Refer to Figure No. 4)

Figure 4 – *Soot-stained concrete surfaces don't necessarily mean that the concrete surfaces exposed to a fire are "fire-affected" to a point requiring repair.*

- All Cracking Observed on Reinforced Concrete Members Subjected to Fire Need to be Repaired – As part of an effort to understand the effects of a fire on a structure, a thorough Condition Assessment is required which would include an evaluation of observed cracking which may or may not have been present prior to the fire event and then just highlighted by surface staining from combustion residue. This evaluation would include determining the width and depth of cracking as well as the pattern and propagation trends. Based on collected data, a licensed professional engineer would then assess whether to address the cracking from a long-term durability perspective or one from a structural standpoint.

- Fire Damaged Concrete Can't be Repaired and Must be Removed and Replaced – As stated above, a thorough Condition Assessment is necessary to understand the physical and chemical characteristics of reinforced concrete structures subjected to fire. Investigative Means & Methods have been established that can determine the depth and extent of fire damage using Non-Destructive (NDT) and Semi-Destructive (SDT) Testing. Information developed during these investigatory efforts will determine the relative "health" of each evaluated structural member and restoration needs if necessary.

Repair Alternatives

After fire-fighting efforts have successfully extinguished the fire at a reinforced concrete structure, Owners have to come to terms with the reality of the effects of the fire and frequently have to make difficult decisions. These decisions can include:

- Do Nothing
- Replace
- Repair (Guesswork)
- Investigate & Repair

Three of the four alternatives listed above provide purely speculative assumptions as to cost and relative safety of the existing damaged structure. Clearly "you don't know what you don't know". Employing an investigative approach at determining the depth and extent of fire damage in a reinforced concrete structure is essentially the only opportunity to establish and prioritize deterioration. Additionally, this effort can also assist in preparing Order-of-Magnitude Repair Costs - especially if this event is associated with an Insurance Claim.

Investigative Approach

When dealing with fire damaged reinforced concrete structures, their evaluation requires a two phase investigative approach. Every fire event is unique ranging from the fuel source, proximity to the structure, duration and fire suppression efforts. The phased approach should begin with a Global-Assessment that examines the event from a broad perspective through testing/sampling in select areas and then extrapolating collected data to the greater area as part of a series of observed deterioration trends. The

Phase 1 Evaluation will typically identify types of fire damage present such as:

- Surface Staining
- Cracking
- Delamination
- Surface Erosion
- Spalling
- Exposed Reinforcing Systems

Limited on-site testing of select damaged structural members would include NDT & SDT techniques that assist in estimating repair quantities and repair costs. Additionally, a Repair Method Statement should be prepared that incorporates Industry Best Practices for repair of fire damaged reinforced concrete. The deliverable associated with a

Phase 1 Evaluation would be a bound report detailing Project Background Information, Investigative Means & Methods, Findings, Analysis, Order-of-Magnitude Repair Quantities with associated Repair Costs.

Unfortunately, all too often, the Condition Assessment process stops here with repairs initiated that evolve into something quite different than anticipated based on the reported findings from the Phase 1 Report. A recommended Phase 2 part of the process is necessary to adequately identify member-specific repair requirements or more simply put, a Member-Specific Assessment. In Phase 2, engineering & contracting services converge at the point of the repair and continue throughout the restoration effort. Phase 2 begins with the premise that the specific repair for a structural member needs to be defined by:

- Performing a localized, member-specific tactile Condition Assessment
- Determines the extent of damage
    - Determines the depth of damage
- Providing a Verifiable Audit Process with integral Owner Approval
    - Level of observed damage
    - Repair program development to fit localized conditions
- Customizing the Repair Program emphasizing QA/QC with auditable performance requirements
    - Excavation & removal of damaged concrete
    - Surface preparation of resultant excavated concrete substrates
    - Repair material placement & curing

The deliverable associated with Phase 2 activities is "As-Built" Documentation that clearly describes what level of damage was encountered at member-specific locations, the repair program selected including materials of repair as well as method of repair and then QA/QC audits to verify repair program approvals and installation compliance.

Reinforced Concrete Fire Investigation Tools of the Trade

Concrete undergoes significant changes when exposed to high temperature events, such as fire, for extended periods of time. As such, how these events affect concrete can be qualitatively and quantitatively assessed via NDT & SDT investigative means & methods. These techniques are applied in select and then specific locations as noted in Phases 1 & 2 of a Fire Damage Repair Program, described above. When beginning an assessment, the initial step is to gather as much original construction documentation as possible to establish an "As-Designed" understanding of the structure(s) both structurally and from an original materials-of-construction standpoint. This important background information can provide clues during Deterioration Mapping activities regarding observed differences of the existing post-fire condition versus original construction details. Original construction documentation also provides compliance information when comparing collected sample specimen testing results to original material specifications.

Once all of the available background information is collected, a Condition Assessment begins by documenting significant visually apparent surface features and deterioration on prepared Drawings with accompanying photographs either on clipboards or in an e-format on tablet-based CAD Drawings. Typical types of deterioration noted can be:

- Surface staining (i.e., soot, efflorescence, etc.)
- Cracking
- Erosion
- Spalling

- Exposed reinforcing systems

At this time, representative regions for NDT & SDT can be selected and areas marked for in-situ testing. Non-destructive field testing techniques for assessing fire damage in reinforced concrete structures include:

- Acoustic Impact Testing (i.e., mechanical hammer sounding – ASTM D4580) for the detection of near-surface internal concrete separations or delaminations.
- Rebound Hammer Testing (ASTM C805) that measures the relative surface hardness of tested concretes or similar concrete mix designs. Fire damage will create "soft paste" conditions rapidly determined by this technique (Refer to Figure No. 5).
- Crack Measurement using calibrated comparators that measure width and relative faulted conditions, if any, of observed cracks.
- Ultrasonic Pulse Velocity Testing (ASTM C597) assesses the relative quality and homogeneity of concrete in-situ based on mechanical stress-wave propagation through solids (Refer to Figure No. 6).
- Impact Echo Testing (ASTM C1383) generates an impact by tapping a small metallic ball causing mechanical stress waves to radiate that encounter other surfaces and rebound, or echo. Processors then accumulate the data and determine the relative internal quality of the concrete based on the stress wave reflections (Refer to Figure No. 7).
- Ground Penetrating Radar (ASTM D6432) utilizes electromagnetic reflection technology to create subsurface images. These images can detect the presence of voids and embedded items such as reinforcing systems and utility conduits.

In association with NDT methods, SDT field methods are also used in the forms of:

- Drill Probes employ a hammer drill with a carbide-tipped drill bit that provides important quantitative information regarding the depth of unsound, fire affected soft concrete conditions. This technique definitively determines the depth of unsound concrete removal at the location tested and based on Technician experience, allows rapid assessment capabilities in "time-is-of-the-essence" repair opportunities (Refer the Figure No. 8).
- Powder Sample collection provides an opportunity to understand the chemical characteristics of the concrete substrate and helps in determining whether to establish a corrosion

Figure 5 – *A Technician employing a Rebound Hammer (ASTM C805) to a fire-affected Column surface to establish surface hardness consistency.*

Figure 6 – *Ultrasonic Pulse Velocity Testing (ASTM C597) on a fire-damaged conventionally reinforced concrete beam. Note both sides of the structural member need to be accessible. Mechanical hammer sounding (ASTM D4580) revealed delaminated conditions along the beam bottom.*

Figure 7 – *Impact Echo Testing (ASTM C1383) on a fire-damaged interior Silo Wall which provided information on internal cracking and relative soundness of the concrete from single side access.*

strategy in association with a structural restoration of the fire damaged concrete member.

- Core/Chunk Sample Extraction (ASTM C42) allows large sample preparation for Laboratory Analysis. Larger specimens provide a more global understanding of the concrete's physical & chemical characteristics in both a damaged and undamaged condition (Refer to Figure No. 9).

Laboratory testing of collected samples can provide substantial insight into the micro and macroscopic properties of the investigated reinforced concrete structure. Petrographic Examination of Hardened Concrete (ASTM C856), after sophisticated sample preparation and analysis, provides qualitative & quantitative information on the existing concrete materials such as:

- depth of carbonation
- water-cement ratio (W/C)
- air content
- aggregate type
- paste-to-aggregate bond quality
- presence/absence of admixtures
- micro-cracking
- other deleterious agents within the concrete mass

Specifically in assessing fire damaged concrete, Petrographers can establish the depth of cement paste alteration and approximate isotherm formation and associated micro-cracking which is helpful in establishing depth of deterioration caused by the fire (Refer to Figure No. 10).

Compressive Strength Testing (ASTM C39) of competent concrete specimens can provide repair strategists with a substrate strength in order to match cementitious repair materials (i.e., "repair-like-with-like") so subsequent to curing, the repair materials will perform compositely with the bonded concrete substrate under load.

Report Preparation

Compilation of data generated during the investigative efforts is an important aspect of capturing the baseline deterioration of the structure exposed to the effects of the fire. It's recommended that the Report be organized into a consistent format that's easily understood as shown below:

- Background, objective and scope
- Investigation summary
- Laboratory summary

Figure 8 – *Drill Probe performed adjacent to core sample location that's used to determine the extent & depth of concrete damage excavation is a quick accurate method of determining repair parameters.*

Figure 9 – *Concrete Core Sampling (ASTM C42) using a wet rotary diamond tipped core-drill.*

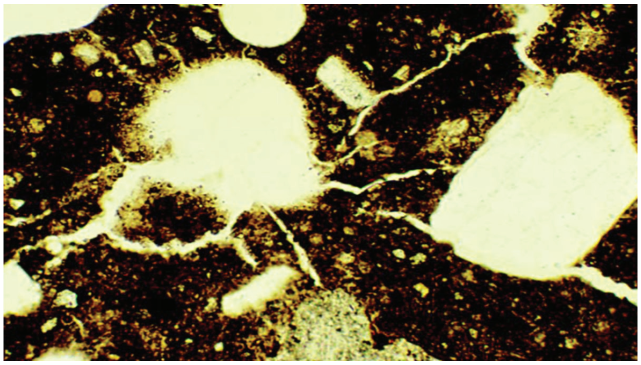

Figure 10 – *Thin-section photo-micrograph from a Petrographic Examination (ASTM C856) of fire-affected concrete revealing extensive micro-cracking in the cement paste matrix5.*

- Data analysis
- Deterioration
- Root cause – effect of fire on reinforced concrete

Repair Program Development and Repair Strategy

Once the root cause has been established as it relates to the individual structural members, a repair strategy can be developed that addresses the full depth of concrete deterioration and integration of new repair materials/details into the composite structural section. It's important to understand that the generalized repair strategy developed may be modified when working on specific structural elements. During a fire event, each structural member experiences a different level of exposure and duration that will vary deterioration extent/depth. As such, each Repair Program should include an Audit/Approval path that focuses on the Damage Level resulting in the selection of the appropriate repair technique. Generally, each structural member repaired will involve a customized repair that will dictate the removal method, surface preparation and ultimately material placement and resultant QA/QC (Refer to Figure No. 11).

Figure 11 – *Fire Damage Concrete Repair QA/QC Control Document providing a verifiable audit trail on-site requiring Hold Points, Witnessing and Sign-Off prior to proceeding with repair activity "milestones".*

Our goal in the repair of concrete members subjected to high temperature fire exposures is to speed the process of returning the structure to service. As part of a successful program is reducing the risk associated with failing to remove all deteriorated concrete materials. How we address this risk is to institute a comprehensive audit trail of detailed means & methods employed by the repair practitioner in an attempt to avoid unnecessary repairs that would generate additional unwarranted costs. Also, a well-developed program will assure all damage is repaired safely, affirming that the structure is safe for return to service and that the Owner maintains a single source of responsibility – from investigation through repair.

Specific fire-damage Repair Techniques associated with reinforced concrete can vary depending on the extent of deterioration, quality of original materials of construction, accessibility and long-term durability. Typically Industry Best Practices follow guidelines established by the American Concrete Institute (ACI) and the International Concrete Repair Institute (ICRI). Once the fire damage concrete has been removed and the resultant concrete substrates prepared, repair techniques listed below can be implemented incorporating repair materials that approximate the physical & chemical characteristics of the existing concrete substrate:

- Cast-in-Place Solutions (Form & Pour or Form & Pump)
- Shotcrete (Pneumatically-placed concrete)
- Trowel-applied Mortars (Thin section, non-structural repairs)
- Pressure-injection of Epoxy resins into significant cracking for in-situ structural bonding

It should be noted that regardless of the repair technique selected, the goal of the restoration is returning the reinforced concrete asset to service in a manner consistent with the original designer's intent (i.e., repair-in-kind).

Conclusion

After the shock and disappointment associated with an unscheduled fire event and its impact on personnel, production and equipment in Commercial, Manufacturing and Industrial Facilities, the next phase in restoring civil/structural assets to pre-fire condition is to more completely understand the expanse and extent of the required repair program. Key to a successful fire-damage restoration is to implement an investigative strategy that Locates, Qualifies and Quantifies (LQQ Method6) the extent of deterioration generated during the fire exposure. The LQQ approach can provide an Owner with information to formulate informed decisions regarding restoration of damaged civil infrastructure. Following up, once a restoration strategy has been developed and initiated, it's critically important to institute a Quality Assurance and Quality Control (QA/QC) Program for Project Site implementation. A well-constructed QA/QC Program employed during repair activities will provide a verifiable audit trail and accountability to assure that all of the fire damaged concrete materials and reinforcing systems have been removed/replaced or augmented. The end product for any successful restoration is the re-establishment of structural integrity providing composite load-carrying behavior between the repair and original parent concrete member/system during service.

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