

Evaluation and Repair of Fire-Damaged Buildings

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Reinforced concrete and masonry structures are protected from fire by the cover that is present over the reinforcement, whereas steel structures are protected with externally applied fire-resistive materials. All three of these types of structures must be properly evaluated after a fire to assess the nature and extent of the damage.

A proper assessment of the structure after a fire event involves both field and laboratory work to determine the extent of fire damage, in order to design appropriate and cost effective repairs. This article presents an overview of how to conduct a forensic evaluation of a fire damaged structure. Two case studies are presented of fire damage evaluation and repair.

Damaging Effects of Fire

The heat associated with fires may vaporize trapped concrete pore water. The lack of continuous voids for pressure relief creates internal tensile stresses that are relieved by cracks and spalls extending to the surface.^[1] Note that spalling may be explosive in higher strength concretes. Additionally, severe heat may cause chemical changes that lead to microcracking (visible only under magnification) and loss of strength and integrity.

The effects of fire on concrete are significantly influenced by coarse aggregate type. Siliceous aggregate concrete retains approximately half its capacity at 1200°F while carbonate and lightweight aggregate concretes exhibit near full capacity at 1200°F.^[2,3]

The thermal protection of reinforcing steel is critical; testing indicates that bars heated beyond 932°F lose significant amounts of yield strength and ultimate strength.^[4,5]

Both typical structural steel (A36 and A992) and high strength alloy steels retain approximately 90% of their strength to nearly 600°F.^[5] Significant dimensional

changes and distortions occur at temperatures above 800°F.^[6]

The heat associated with a fire can cause many types of changes to structural steel elements such as member deformation. Besides large deformations, other less obvious changes can occur at higher temperatures such as loss of normalized microstructure; stress relieving or sensitization of stainless steels; high residual stresses; or embrittlement due to rapid cooling^[6] associated with fire fighting efforts.

Process

The evaluation determines the nature and extent of the fire damage and whether repairs are required. This process involves (1) determining when to observe the fire-damaged structure (both before and after cleaning), (2) how to evaluate the post-fire conditions (visually, non-destructively, or destructively), and (3) assessing the structure to determine what, if any, repairs are required.

The repair process involves (1) evaluating the options (remove and replace, salvage/repair, or no action), (2) selecting the repair materials (concrete, steel, or fiber reinforced polymers), and (3) detailing the repairs (preparation, installation, and quality control). *Figure 1* summarizes the process.

Unless you are working with the fire department to fight the fire, no one should enter the structure until it is safe to do so. Fire damage to the structure is

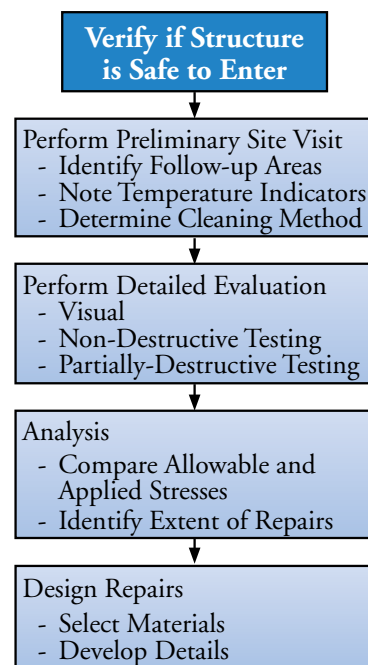


Figure 1: Process Flow Chart

Table 1: Physical Effects of Temperature on Concrete^[8]

Temperature	Color Change	Changes in Physical Appearance and Benchmark Temperatures	Concrete Condition
0 to 550 °F (0 to 290 °C)	None	Unaffected	Unaffected
550 to 1100 °F (290 to 590 °C)	Pink to red	Surface crazing: 570 °F (300 °C); Deep cracking: 1020 °F (550 °C); Popouts over chert or quartz aggregate: 1070 °F (575 °C)	Sound but strength significantly reduced
1100 to 1740 °F (590 to 950 °C)	Whitish Grey	Spalling, exposing not more than 25% of reinforcing bar surface: 1470 °F (800 °C); Powdered, light colored, dehydrated paste: 1650 °F (575 °C)	Weak and friable
1740+ °F (950+ °C)	Buff	Extensive spalling	Weak and friable

not always obvious. By entering as soon as practical, the engineer can uncover hidden distress and observe the collateral damage to finishes and contents. If the engineer observes contents that are not burned beyond use, the steel is not expected to be damaged. Collateral damages frequently provide good indications of maximum fire temperatures.

Evaluation

The three stages of evaluation are visual assessment, non-destructive testing, and partially-destructive testing.

STAGE 1

Visual Assessment – Cleaning

Soot hides most cracks, spalls, and distortions in the structure. The structure may be cleaned by means of dry ice blasting, grit blasting, water blasting, or chemical washing. Chemical wiping or dry ice blasting tends to generate the least collateral damage to the structure. Grit blasting tends to produce large amounts of blasting medium. Water blasting can cause collateral damage to finished areas below the fire (beyond the firefighting water damage).

Visual Assessment – Coloration

Fires consume timber based construction materials from the outside in; the charred exterior material helps protect the interior material. The presence or absence of charred/burned timber can help determine the fire's temperature and duration.

Intense heat may cause chemical reactions that form crystals or change the properties/color of the matrix and/or aggregates in concrete^[8,9]. *Table 1* summarizes the changes in concrete (color, surface appearance, and condition) by temperature and can be used to estimate the effect of the fire. Additionally, the rapid cooling of the concrete by firefighting water can cause thermal cracking and superficial surface spalls.

Proper evaluation of steels subjected to fire typically requires estimating the temperature and duration of the fire. For clean unpainted steel, a yellowish brown color indicates a temperature of 460-480°F while a blue color indicates a temperature of 600-640°F; other tempering colors are provided in the referenced API document^[6].

Visual Assessment – Deformation

Deformation of structural members and associated materials (coatings, pipes, et cetera) can provide valuable information to develop a

heat intensity map. *Table 2* provides common temperature indicators.

STAGE 2

Non-Destructive Testing – Concrete

The extent of delamination can be determined by means of chain dragging for large horizontal areas such as slabs, and by means of hammer

sounding for vertical and overhead surfaces. Impulse response can be used to rapidly screen large areas for potential damage. Impact echo testing can also be used to determine the depth and extent of internal fractures. Finally, rebound hammers are frequently used to compare the surface hardness of concrete to locate potential damage.

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Table 2: Physical Effects of Temperatures on Various Materials^[6,7]

Material	Examples	Condition	Temperature
Polystyrene	Foam insulation; light shades; handles	Softens	120 to 140 °F (50 to 60 °C)
	Curtain hooks; radio containers	Melts and flows	250 °F (120 °C)
Polyethylene	Bags; film	Shrivels	120 °F (49 °C)
	Bottles; buckets	Softens and melts	150 °F (66 °C)
Vinyl-based paints	Structural steel paint	Melts, flows, bubbles, or burns	250 °F (120 °C)
UHMW / HD Polyethylene pipe	Water and waste pipes	Melts, flows, bubbles, or burns	375 °F (190 °C)
Lead	Plumbing lead; flashing; storage batteries	Sharp edges rounded or drops formed	550 to 650 °F (300 to 350 °C)
Zinc	Plumbing fixtures; flashing; galvanized surfaces	Drops formed	750 °F (400 °C)
Aluminum	Small machine parts; brackets; toilet fixtures; cooking utensils	Drops formed	1200 °F (650 °C)
Molded glass	Glass block; jars and bottles; tumblers; solid ornaments	Softened or adherent	1300 to 1400 °F (700 to 750 °C)
		Rounded	1400 °F (750 °C)
		Thoroughly flowed	1450 °F (800 °C)
Sheet glass	Window glass; plate glass; reinforced glass	Softened or adherent	1300 to 1400 °F (700 to 750 °C)
		Rounded	1450 °F (800 °C)
		Thoroughly flowed	1500 °F (850 °C)
Silver	Jewelry; tableware; coins	Drops formed	1750 °F (950 °C)
Brass	Door knobs; furniture knobs; locks; lamp fixtures; buckles	Sharp edges rounded or drops formed	1650 to 1850 °F (900 to 1000 °C)
Bronze	Window frames; art objects	Sharp edges rounded or drops formed	1850 °F (1000 °C)



Figure 2: Slab separation and joist spalling.



Figure 3: Heat damage of seats at level above fire.

Non-Destructive Testing– Steel

Non-destructive evaluation techniques for steel structures include distortion measurements, plumbness or straightness checks, and hardness testing. If the member distortion is minor, it is unlikely the member was exposed to a temperature of more than 1200°F for any length of time and therefore no consequential metallurgical changes will occur^[11].

Measurements of distortion, such as buckling of restrained plates and out-of-plumbness, can provide an indication of maximum temperature reached.

Visual inspection of connections that are to remain is critical since connections may have fractured due to the fire event^[11]. Weld inspection techniques such as ultrasonic testing, magnetic particle testing, and dye penetrant testing may also be useful in determining the integrity of welded connections.

Hardness testing aids in determining the loss of tensile strength in cold formed and structural carbon steels and, to a lesser extent changes in ductility and toughness. ASTM A370-05, Standard Test Methods and Definitions for Mechanical Testing of Steel Products, provides guidelines for correlating

hardness numbers with approximate tensile strengths^[12]. Scaling of carbon steels typically begins above 1000°F and can affect hardness readings^[6]. Above 1200°F the surface will develop a coarse, eroded surface markedly different from mill scale^[13].

Partially-Destructive Testing – Concrete

The primary destructive tests for concrete are compressive strength testing and petrography. The compressive testing gives a general indication of whether or not the concrete meets the design requirements. Strength tests should be correlated with petrographic examinations of nearby cores. The initial heating effects of the fire dessicate the concrete and may cause a moderate increase in the breaking strength of cylinders.

The internal condition of fire damaged concrete needs to be evaluated by petrography. This involves both macro and microscopic

examination of dyed concrete thin sections to determine aggregate and paste mineralogy and microstructure. Petrography provides information on cracking such as orientation and location, changes in color, carbonation, paste-aggregate bond, water/cement ratio, air content, desiccation, and depth and extent of damage.

Partially-Destructive Testing – Steel

The primary destructive tests for steel are tensile tests to determine yield and ultimate tensile strength. Microscopic examination of fracture surfaces are not commonly performed for fire damage evaluations.

Engineering Analysis

The assessment phase compares the findings of the evaluation phase (damage plots, temperature plots, and allowable stresses based on non-destructive and/or destructive testing) with the analysis findings to determine if the applied stresses in the various elements exceed allowable levels. This then determines the extent, if any, of required removals, replacements, and/or repairs. Based on the results of the assessment, repair materials can be selected, details developed, and repairs installed.

Fire Damage Repairs

Typically, repair materials are similar to the original construction materials. Timber structures may be repaired with new timbers or composites of steel and timber members, and steel structures are normally repaired with steel. Both concrete and masonry structural elements are frequently repaired with fiber reinforced polymers (FRP) or externally bonded steel members using epoxy adhesive.

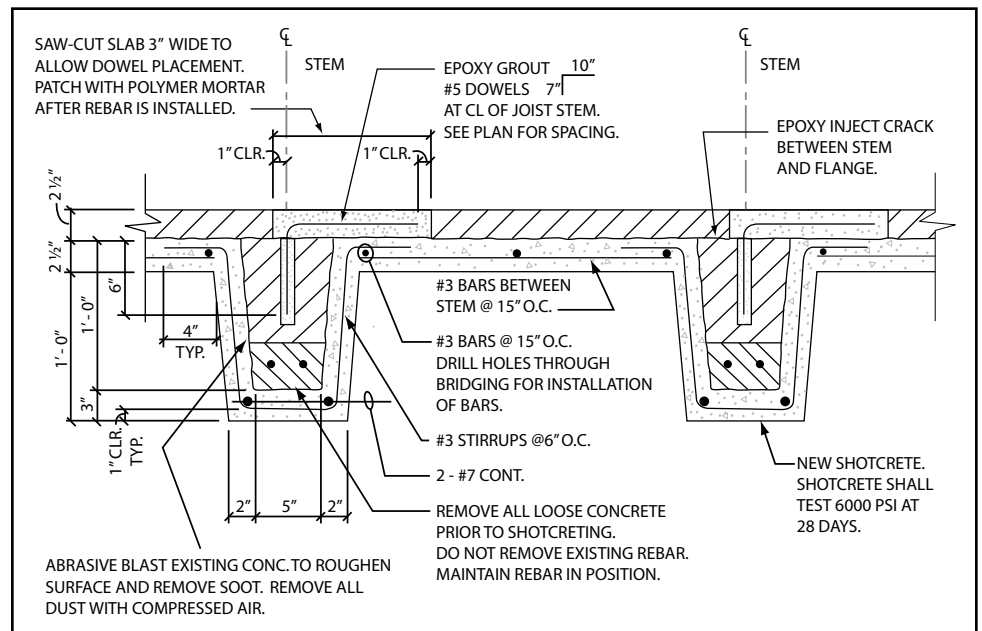


Figure 4: Repair detail for slab-joist separation.

Concrete structures are occasionally repaired with shotcrete as well. Selecting the appropriate repair material is a critical step in the repair process. The repair material must be compatible with the base material, project needs, technical resources available, financial constraints, and multiple other project specific criteria.

Case Studies

Two case studies are presented to illustrate various types of structural damage and repairs worked on by the authors^[10]. The first summarizes the assessment and repair for arson damage to a reinforced concrete stadium structure. The second addresses the evaluation and repair of damage to a steel framed office building.

Case Study 1: Stadium Fire

An arson fire occurred on an elevated level of a reinforced concrete stadium structure. After the fire department approved the area for entry, initial observations were made. The fire severely damaged the concrete in an area approximately 25 feet by 25 feet above the fire; the concrete joists were deeply spalled, the slab separated from the joists, and severe cracking was present (Figure 2).

The fire was intense to the extent that the seating area directly above the fire suffered heat damage (Figure 3).

Destructive testing indicated that the strength of reinforcing steel and some concrete above the fire was compromised. Repairs were designed to rebond the slab and joists using L-shaped dowels to hook the slab and joist webs together. The load carrying capacity of the effected slabs and joists were repaired by means of encasing external reinforcement (bars and stirrups) with shotcrete applied to an intentionally cleaned and roughened surface (Figure 4).

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Figure 6: Buckled metal deck. Note separation of concrete from metal deck through exploratory opening.

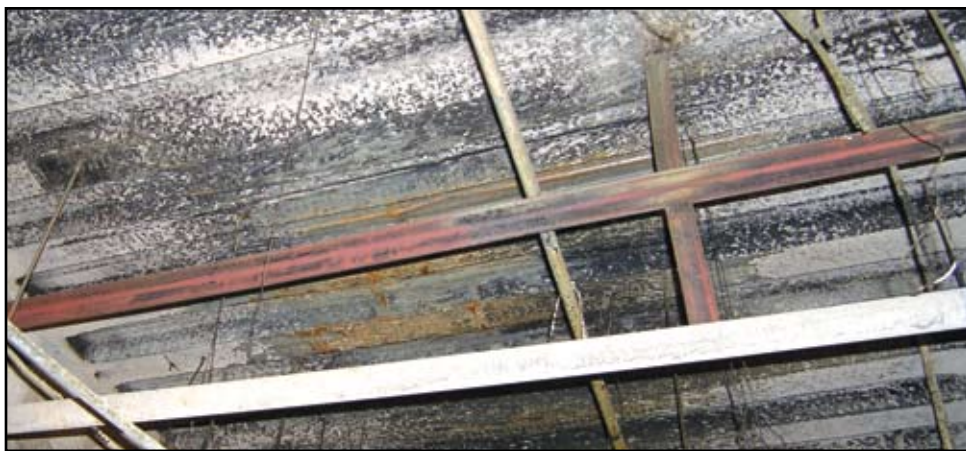


Figure 5: Interior damage due to fire.

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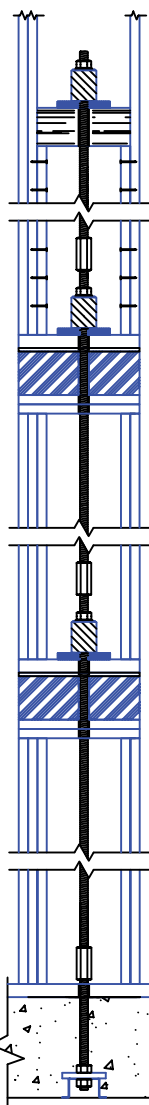
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Figure 7: Collateral damage to plastics.



Figure 8: Structural repairs to limit floor slab displacements.

Case Study 2: Occupied Steel High Rise Fire

Fire occurred in an occupied space of a steel framed high rise. The steel framing was protected by a sprayed fire resistive material. The exposed metal deck supports a composite concrete floor system. (Figure 5, page 21). Heat from the fire caused some buckling of the metal decks near the fire (Figure 6, page 21) and deformation of plastic magazine racks (Figure 7) in an adjacent room not directly exposed to the fire.

The evaluation effort included steel hardness readings of the structural steel framing members. In addition, concrete cores were extracted from the floor slab where the fire occurred and in the deck directly above the fire for compression testing. No testing was considered necessary in the adjacent room with deformed plastic due to the low temperature indication. Test results confirmed that steel hardness was in the expected range to indicate minimal heat damage to the steel frame. Concrete cores indicated that compressive strengths exceeded design requirements.

The assessment concluded that the steel frame did not require repairs. However, to prevent displacements of the separated concrete slab above the metal deck, structural repairs were required (Figure 8). The repairs included adding new beams to support the metal deck and the addition of grout to fill the voids between the concrete and metal deck.

Conclusions

All structures subjected to fire should be evaluated in a systematic manner to determine the extent, if any, of required repairs. The intensity and duration of the fire can be estimated by observing the collateral damage; a variety of testing methods and tools are available to evaluate the effects of the fire on both the materials and structural elements. These evaluations, combined with an engineering analysis, allow effective and economical repair details to be developed and installed as needed. ■

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