

Nondestructive Testing Verifies Quality of Repair

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Nondestructive testing (NDT) has become an important tool in evaluating questionable structures or individual building components. The information gained from NDT is critical for determining the extent and severity of construction defects or making damage assessments. It provides a basis for assessing the condition of columns, beams, foundations, walls, etc., and helps in developing a sound corrective response.

Advancements in personal computing have made the personal computer (PC) a vital tool of the nondestructive testing industry. A PC increases the flexibility and speed with which NDT crews can gather data, which allows them to examine more areas in less time for less cost. These factors have made NDT more valuable to owners, engineers, and contractors who need to correct construction problems quickly.

When building components exhibit problems such as low strength, excessive voiding, improper cover over reinforcing steel, or damage due to fire, investigators commonly take material samples for analysis. Extracted samples, such as concrete cores or reinforcing steel specimens, are very useful, but extracting samples is destructive and may create a need to repair sampled areas. This is why fewer

samples are often taken than ACI and ASTM guidelines recommend. When a testing program includes both destructive samples and NDT, far fewer samples generally will be required. This saves time and results in less damage to the structure, while actually covering a much greater portion of the structure. In summary, combining NDT with the testing of actual material samples in a properly executed test program and engineering review is the best way to assess the causes, and not just symptoms, of a structural defect. It offers the best basis for developing a repair approach to correct defects.

Assessing a Fire-Damaged Garage

CTLGroup recently evaluated a parking garage that was severely damaged by fire. In the evaluation program, nondestructive testing provided information on changes in precast panel stiffness and mobility as a result of the fire damage. This information was used in conjunction with the testing of concrete cores and steel reinforcement specimens as a basis for the owner's repair approach. A follow-up test program was also conducted after completion of all repairs to assess the improvement in panel performance after application of a silica fume modified repair material.

The garage was approximately 120 x 260 ft (37.5 x 73 m) in plan and contained six levels of parking. The garage walls consisted of 8 in.-thick (200 mm) precast concrete panels. The garage was surrounded by wood-framed condominiums that were still under construction when the fire occurred. The fire resulted in considerable cracking and spalling of the concrete at the exterior face of the precast panels.

The panels were precast of normalweight concrete about 2 to 3 months before the fire. At this early age, the panels still retained considerable internal moisture, and this moisture, when exposed to the fire's intensity and speed, contributed to the severe spalling exhibited by the structure. The garage walls were two panels high. The lower-level panels were reinforced with two layers of 4 x 4 in. (100 x 100 mm) W3/W3 WWF, and the upper level panels were reinforced with one layer of 12 x 6 in. (300 x 150 mm) W3/W5 WWF. The reinforcing bars were 60 ksi (414 MPa) grade bar.



Overall view of garage wall at entrance. Debris is still in place at the time of the site visit, preventing visual inspection of exterior surfaces of lower panels. However, NDT proceeded as planned from the interior surfaces

The NDT team evaluated the condition of the garage panels after the fire and again following the repair. Investigators used impulse-response (I-R) test methods in the testing program (see sidebar). All panels that had been exposed to the detrimental effect of the fire were tested. Severely damaged panels that the owner had immediately designated for replacement were sampled to identify a “worst case” test signature. Fire-induced spalling of the exterior faces caused section loss in the panels. Therefore, investigators tested the panels from their interior faces to evaluate the resulting reduction in stiffness and increase in mobility.

The NDT program covered most of the exposed surface area of the precast panels. A grid pattern was established to test the panels at 2 x 2 ft (0.6 x 0.6 m) intervals both vertically and horizontally. In addition, cores were extracted from almost every panel to determine compressive strength, measure loss of panel thickness due to spalling, determine modulus

of elasticity, and perform petrographic examinations. Finally, mechanical properties of the reinforcing steel were tested in accordance with ASTM A 370 “Standard Test Methods and Definitions for Mechanical Testing of Steel Products.” The combination of NDT and destructive laboratory testing yielded enough information for the team to develop the repair approach with full confidence. The repair plan addressed the need for surface preparation, removal of reinforcing steel in heavily spalled areas, and procedures to achieve adequate bond of the shotcrete repair material.

The post-repair impulse-response test was performed after the repairs to the panels were completed. The impulse-response test was performed at the same test point locations of the previous test so as to compare the pre- and post-repair results. The post-repair results showed that the high mobility values recorded before the repairs (areas noted in yellow, orange and red on the pre-repair plot) were



Overall view of portion of the garage where damage was severe and many panels were replaced. Only limited testing was conducted on these panels



Overall view of typical interior panel faces. Core holes are visible. The inside faces of the panels were generally unaffected by the fire and provided an excellent surface to send and receive impulse signals



Common degree of damage suffered at the precast panel exterior face due to fire. Spall depths of up to 2-1/2 in. (6 cm) exposing steel were not uncommon



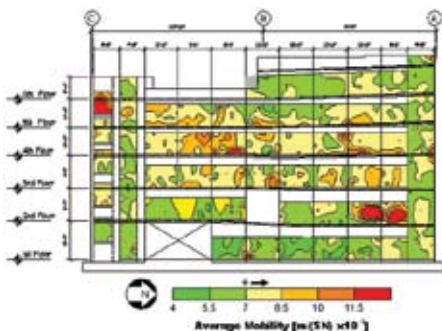
Impulse-response testing on the inside surface of the panel

Impulse-Response (I-R) Testing

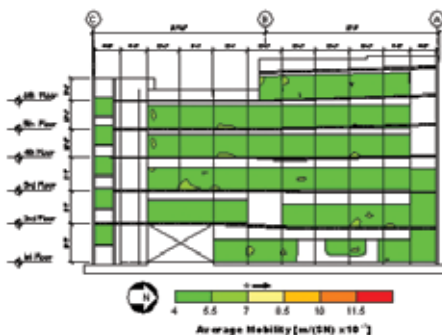
The I-R method uses a low-strain impact to send a stress wave through the tested element. The impactor is usually a 2.2 lb (1 kg) sledgehammer with a built-in load cell in the hammerhead. The response to the input stress is normally measured by a velocity transducer (geophone). Both the records for the hammer force and the geophone velocity response are processed in the field computer to obtain a transfer function, referred to as the mobility of the element under test. The test graph of mobility plotted against frequency over the 0 to 1 kHz range contains information on the condition and the integrity of the concrete in the tested elements.

Sound concrete in plate-like structures such as slabs, walls, and bridge decks typically gives a constant value of I-R average mobility, which is inversely proportional to the concrete element thickness. Poor concrete compaction and honeycombing cause the value for average concrete element mobility to increase, usually accompanied by a rising mobility value with increasing frequency. A reduction in dynamic stiffness is often present too. Delamination of concrete along reinforcing bar planes is registered in the I-R test by a significant increase in average mobility, accompanied by a large reduction in dynamic stiffness and a high mobility at low frequencies.

The I-R test produces a principal parameter, "average mobility," which is defined as the result of structural surface velocity responding to the impact divided by the force input ($(\text{m/s})/\text{N} \times 10^{-7}$). The mean mobility value over the 0.1 to 1 kHz range is directly related to the modulus, density, and thickness of a plate element, for example. In general, the presence of any internally delaminated layer, weakened layer, cracking, unconsolidated concrete, or reduced effective thickness will result in an increased average mobility value. Conversely, a sound concrete element without distress will have a low average mobility value.



I-R plot of panels showing numerous areas of distress (yellow, orange, and red). Testing was performed on the inside surface prior to any repairs



I-R plot of the panels after the repairs were performed. Plot showed uniform average mobility values. The high mobility values recorded before the repairs were no longer present, indicating that the repairs were satisfactory

no longer present, indicating that the repairs were satisfactory. The two I-R plots depict the mobility of the wall before and after the repairs.

Nondestructive testing can be used both as a tool to verify problems and also as a quality assurance tool. Testing can be performed quickly and cost-effectively as demonstrated by this case study. As a quality assurance tool, nondestructive testing can be used to demonstrate to the owner that the repairs are properly installed.



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George W. Seegebrecht is a senior engineer for CTLGroup. Seegebrecht has broad experience consulting on issues relating to concrete performance, design, and repair. He has managed projects investigating a wide range of distressed or deteriorated structures, as well as developing repair alternatives, preparing repair specifications, and monitoring repair work. Seegebrecht also is a frequent seminar speaker on topics including troubleshooting concrete problems, concrete durability, shotcrete, concrete repair, concrete cracking, surface defects, and placing and curing concrete in extreme temperatures.



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Note from the Author:

The impulse-response (I-R) test is a rapid, nondestructive test method that has been successfully used to evaluate the presence and extent of debonded concrete topping layers or repairs from their substrate. The I-R test has been used alone or in combination with destructive and other nondestructive test methods to assess concrete or shotcrete repairs of structural elements, cooling towers, chimneys, etc.

In the example of the fire-damaged structure shown in the article, destructive testing by doing bond pulloff (ASTM C 1583-04, "Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength of Concrete Repair and Overlay Materials by Direct Tension [Pull-off Method]") of the shotcrete overlay was used to confirm indications from the I-R testing that the shotcrete was well bonded. In ACI 228.2R-98, "Nondestructive Test Methods for Evaluation of Concrete in Structures" (ACI Committee 228),¹ the I-R method has been listed as an approved test method for assessing damaged and repaired structures. The I-R test method has also been upheld as an approved method in litigation cases. In ACI 228.2R-98, Table 3.1, Nondestructive Test Methods for Determining Material Properties of Hardened Concrete in Existing Construction, has I-R listed as a secondary method, applicable for evaluating fire-damaged concrete.

Because shotcrete is frequently applied onto surfaces where only one side is accessible (pool excavations, rock excavation, stay-in-place forms, repairs) this method may be particularly useful relative to other NDE methods.

As shown in the schematic in the article, an I-R survey was conducted of damaged structures and conducted again after application of repair material (shotcrete) to show the improved structural behavior following the repair. This method allowed wide nondestructive test coverage in relatively little time.

The test method uses stress waves to determine stiffness and mobility of a member. If cracks or voiding exists within the cross section of the member, it would be more mobile and less stiff (relative to a condition without any defect). If no baseline behavior is available, however, this initial behavior can be compared to the behavior after the shotcrete has been applied. If the shotcrete is properly bonded to the substrate (could be either concrete or shotcrete), the mobility will decrease and the stiffness will increase.

References

1. ACI Committee 228, "Nondestructive Test Methods for Evaluation of Concrete Structures (ACI 228.2R-98)," American Concrete Institute, Farmington Hills, MI.

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