Non-Destructive Testing of Reinforced Concrete

By Gerard C. Feldmann, P.E.

Reinforced concrete has been used for structures of every type and size for over a century. Concrete structures built in the beginning of the twentieth century are still in service, but these are generally massive works of unreinforced concrete. The Achilles heel of concrete is the steel reinforcement that is embedded in it. Although there are deterioration mechanisms that attack the concrete matrix directly, it is most often the corrosion of the embedded reinforcing steel that leads to its visible deterioration (*Figure 1*).

Non-destructive testing is generally described as testing that imparts little or no damage to the concrete, although it usually requires sampling or removing a small amount. Such testing indicates whether any chemical contamination has occurred and reveals the concrete's electro-chemical state. With this information, the engineer can design a remedial repair program.

Figure 1: Deterioration of Concrete Due to Rebar Corrosion.

Investigation

Reinforced concrete has been used in construction for over a century. Tension reinforcement helps control cracking and provides ductility. Codes have specified minimum concrete clear covers for years, depending on exposure. In the last 30 or so years, however, more attention has been given to chemical exposure, both internally and externally. Common internal sources of contaminants include the use of beach sand or chloride-containing admixtures that speed set time. Common external contaminants generally come in the form of chlorides, either naturally occurring from seawater exposure or man-made from deicing salts, atmospheric carbon dioxide or chemical processes.

The high pH of the interior of a reinforced concrete element protects uncoated steel from corrosion. A protective layer forms on the surface of the steel. Contaminants such as chlorides and carbonation break down this protection and create conditions conducive to corrosion. Corrosion of the steel will occur if water and free oxygen are present. The corrosion by-products, which form rust, expand the size of the steel, creating large internal bursting stresses, which then cracks the concrete. Spalled concrete with visibly corroding reinforcement is the end result of this process.

Testing Methods

There are many non-destructive tests that can be performed. The most common test methods are listed below, with a short description of the test method and an explanation of the results. The list is not exhaustive. These tests are for uncoated carbon steel reinforcement, either reinforcing steel or prestressing strands. Epoxy coated steel or plastic-sheathed post-tensioning strands have protective coatings that electrically isolate them, and thus these tests will not give meaningful results. These tests are typically used in the initial evaluation of a structure.

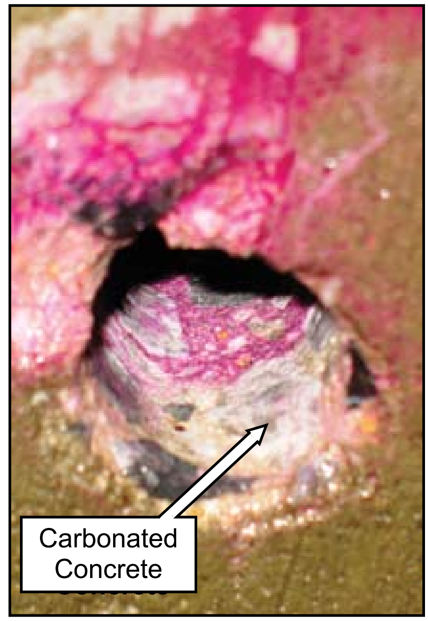

Figure 2: Carbonation Testing of Concrete.

The results may require more sophisticated methods of investigation, such as x-ray, linear polarization or petrographic analysis.

Some non-destructive test methods listed are totally non-destructive, while other methods require only drilled holes. Test areas in a structure should incorporate as many of the listed tests as possible to give a complete picture of the internal properties of the concrete.

Carbonation

This test measures the pH of the concrete. Freshly placed concrete normally has a pH between 12 and 13, which provides protection of the embedded steel and prevents corrosion even in the presence of water and oxygen. Concrete is considered carbonated when the pH falls below 11.5. At this pH level, only moisture is needed to initiate corrosion. Phenolthalein solution is a typical color changing indicator that is used to perform the carbonation tests. The test solution is colorless at and below a pH of 8.2 and is pink/purple at a pH greater than 10.0. Other indicators are available that measure different pH intervals. One commercially available indicator measures pH from 1 to 14 with a rainbow spectrum.

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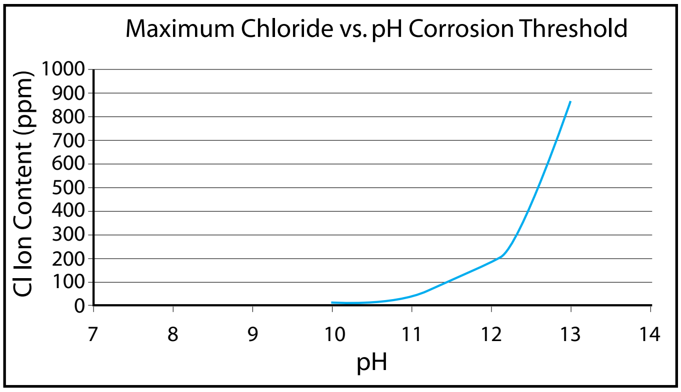


Figure 3: Graph of Chloride Ion/pH for Corrosion Theshold.

Testing is performed by exposing a freshly broken face of a concrete surface. This is accomplished either by chipping off a small piece of concrete with a rock hammer and chisel, if the carbonation is shallow, or by drilling a hole with an electric hammer drill. The broken surface is washed with distilled water to remove dust that may contaminate the surface. The indicator solution is then sprayed on and the results recorded (*Figure 2, page 13*). The depth of the probe will need to be increased if only carbonated concrete is found.

Chloride Ion Content

Deicing salts, on or carried into structures, penetrate the concrete, eventually initiating the corrosion of any uncoated embedded reinforcement. The accepted threshold value for chloride content in concrete is 300 parts per million (ppm), above which active corrosion in the embedded steel will occur. This threshold becomes lower if the concrete is carbonated. See *Figure 3* for a chart of pH level vs. chloride threshold level.

Testing is performed by taking powder samples from the concrete with a small electric impact hammer to create a profile of chloride content versus depth. The sampling should be taken at approximately 1-inch intervals to a depth below the nearest level of reinforcement. The chloride environment where the rebar is located is important to determine the durability of the structure. Samples should be taken from visibly deteriorated areas, from visibly "clean" areas, and from areas where exposure to contaminants is unlikely, such as the uncracked soffit of a parking structure. This last sampling area is necessary to establish background levels of chloride. There is always some level of chloride present in concrete that comes from the individual components. This is allowed, but limited, by codes.

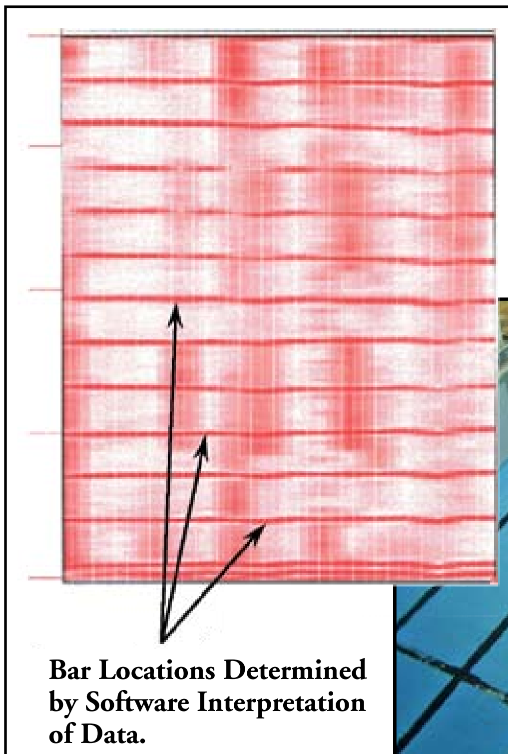
Ground Penetrating Radar (GPR)

Based on reading echoes of pulsed electromagnetic waves, radar measures the difference in materials by acoustic density. Internal flaws can be measured, as well as the reinforcement and thickness of the member. The cost of this testing has decreased in recent years, and new software has reduced the amount of interpretation required by the operator. GPR is expensive, but is cost-effective for testing large areas. Limitations include "shadowing" of lower layers of reinforcement and the inability to determine bar size. See *Figure 4* for a sample of GPR output on a concrete structure.

Half-Cell Potential Testing

The internal environment of concrete needs free moisture and ions to create the conditions necessary to allow corrosion. Half-cell potentials estimate the susceptibility of the reinforcing steel to corrosion activity. A copper-copper sulfate electrode is used as the reference cell.

Testing can be performed on the top or on the underside of a concrete structure. The test area must contain reinforcement that is electrically continuous throughout. At the limits of the test area, electrical continuity is confirmed by drilling two holes to the reinforcing mat and then testing the mat for zero



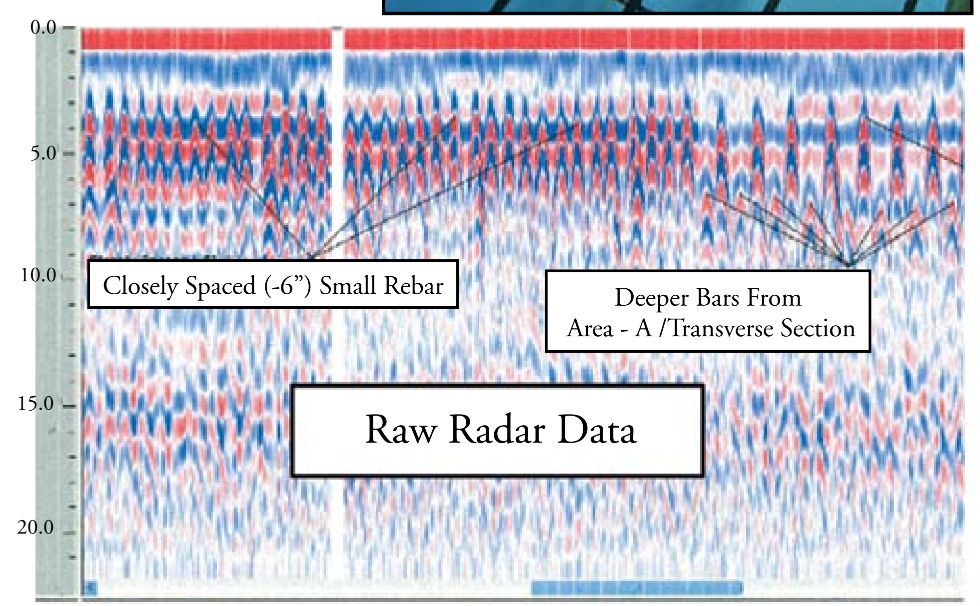


Figure 4: Radar Testing and Output.

resistance. Test readings are generally taken on a grid spacing of 3 to 4 feet, with a total test area of at least 300 square feet. Prior to testing, the concrete surface is locally wetted down on the test grid in order to have moisture available in the concrete matrix. Readings are made by connecting one multitester lead to the reinforcing mat and the other to the reference half-cell electrode, which generally has a sponge attached to it in order to give it a good electrical contact with the concrete and also to maintain the required moisture. Testing equipment that stores the data and creates potential maps is commercially available.

Half-cell potential readings that are more negative than -350 millivolts (mV) indicate a 90% probability of corrosion activity, while readings that are more positive than -250mV have a 90% probability of no corrosion activity. Readings between -250mV and -350 mV have an unknown probability of corrosion activity.

Half-cell testing is performed in temperatures above 40 degrees F in order to obtain meaningful results. Reference standard ASTM C876 has a correction factor for temperatures between 40 and 72 degrees F. The surface of the concrete needs good electrical contact for this testing to be meaningful. This requires that coatings, such as waterproofing membranes or sealers, must be removed. Readings will vary with the internal humidity of the concrete matrix and are sometimes erratic for very dry concrete. See *Figure 5 (page 16)* for a typical half-cell potential plot.

Impact-Echo

Impact-echo is a method that non-destructively finds internal flaws (such as cracks, honeycombing, and others) in concrete structures using transient stress waves. Software can be used to speed up the interpretation of data. Limitations are a relatively smooth surface for testing, a maximum effective testing depth of 3 feet, and a poor resolution of small flaws and objects at this depth.

The impact echo method can also determine the concrete thickness. This requires testing at a known thickness to calibrate the concrete wave speed. *Figure 6 (page 16)* shows output from impact-echo testing.

Reinforcement Location

The concrete cover over the reinforcing steel is typically the best way to extend the service life of the structure. "More is better" because it takes longer for contaminants to reach the level of the reinforcing steel.

Reinforcing steel is generally located by electro-magnetic means. These devices are specialized metal detectors that have been calibrated for concrete reinforcement. However, there are limitations for these devices. Sometimes non-structural steel, embedded or externally mounted, interferes and/or prevents locating the reinforcement. To locate isolated reinforcing bars, most available electromagnetic devices are limited to a concrete thickness of about 12 inches. These devices can only find the nearest layer of reinforcement and cannot resolve closely spaced bars as individual bars.

GPR can be used in this instance to save time for determining reinforcement over large areas, or determining reinforcement in areas of externally mounted steel that would otherwise interfere with electromagnetic devices.

Sounding

The corrosion of embedded reinforcement results in bursting stresses that create delaminations, which in turn create thin hollow planes parallel to the surface. These hollow areas can be found by using other tests listed here, but the simplest of the tests requires only a rock hammer, a length of chain or a piece of rebar. The concrete is impacted and the resulting sound is sampled for "hollowness". The difference in tone between solid and delaminated concrete is generally easy to detect. There is, however, some difficulty in hearing deeper delaminations due to the mass and stiffness of the overlying concrete. The use of a small sledge hammer can sometimes help here.

Sample Structure

Let us now assume that we receive a call regarding a two-level, reinforced concrete parking garage, with a one-way slab and beam framing system that is experiencing deterioration. We are told that the garage is approximately 25 years old, and that it has extensive visible cracking, leakage and spalling. No original drawings are available. The owner is requesting a survey to determine repairs and long-term serviceability needs. A walk-through of the structure prior to outlining the testing program is essential. This will give the engineer a sense of the conditions and will guide the testing methods that will be used.

The walk-through and quick survey of the garage reveal a large number of delaminations and spalling of the concrete slabs, both at the top and at the bottom. No previous repairs are noted. With the field conditions and age of the structure in mind, the deterioration at first glance appears to be related to deicing salts and, possibly, carbonation contamination. A recommended testing program will check for carbonation, chlorides, half-cell potentials, and rebar location.

As with any sampling method, a minimum number of samples are taken in order to give a level of confidence that the overall condition of the concrete is well-represented.

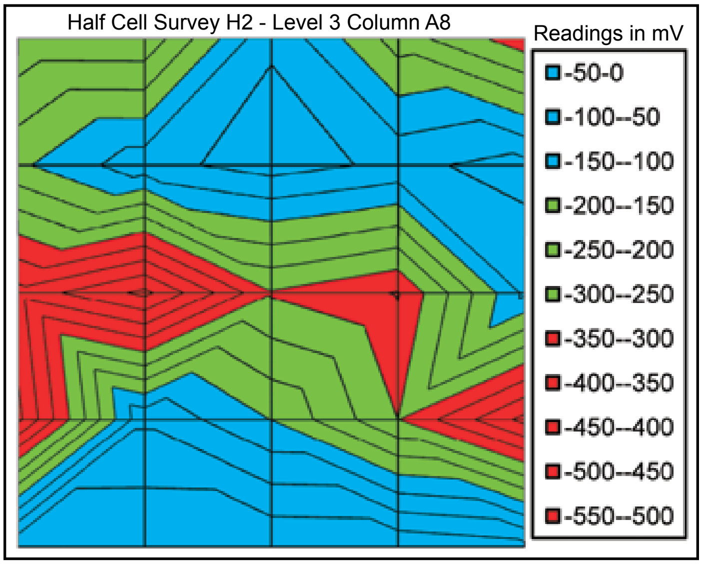


Figure 5: Sample Half Cell Potential Plot. Grid Indicates Sample Locations. Red Areas are Above the Threshold, Blue is Below and Green is Unknown.

There is always a balance here. Statistical analysis can be useful, but experience also helps. Samples from concrete placements separated by construction joints are recommended to determine if the contamination varies by time frame of concrete cast.

After the dimensions of the garage are established, the determination of the slab thickness and typical reinforcement is performed. Locating the reinforcement by non-destructive electromagnetic means is simplest, but time consuming. GPR equipment could determine the layout the quickest, but equipment costs are high, bar sizes cannot be distinguished, and some of the equipment can only be used by a trained technician. Electromagnetic rebar locating devices are usually able to estimate the bar size within one increment for grades 40 and 60. Prestressing steel size, material and cover data is generally not included by the device manufacturer, but the device can be calibrated with field data to allow a large non-destructive survey of prestressing steel. Destructive probing is recommended for spot checking the bar size.

The concrete environment is tested next. Test locations should be random, but need

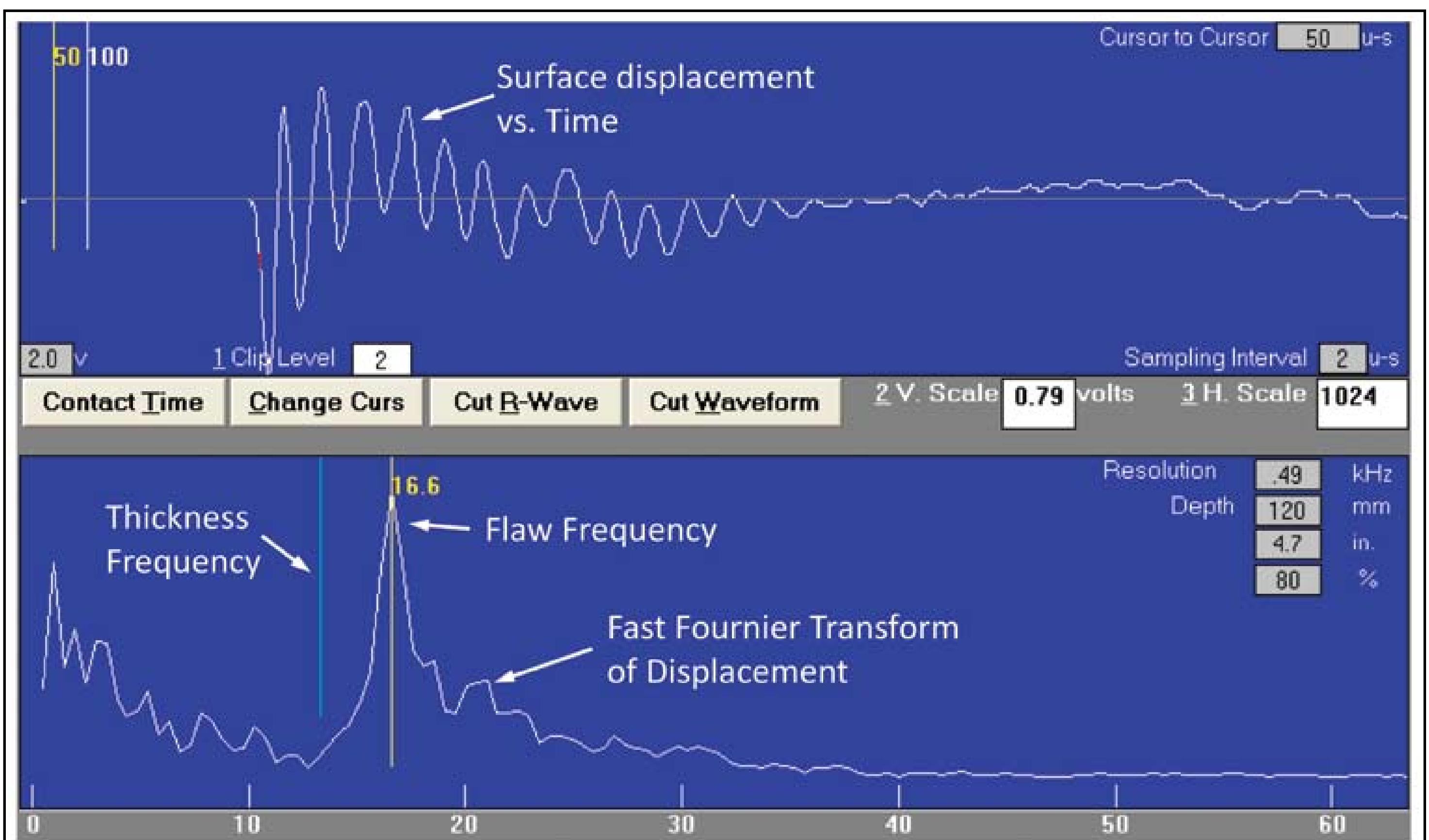


Figure 6: Sample Output from Impact Echo.

to include both visibly good and bad areas of the structure in order to determine the limits of the internal chemistry and contaminants. Chloride ion content, carbonation, and half-cell potential tests, as well as reinforcement clear cover measurements, are performed at the same location to reveal a picture of the concrete condition in the test area. Concrete powder samples are taken for chloride testing. Simpler tests, such as carbonation tests, are easily performed and, thus, can be more numerous in the test area. Additional chloride ion and carbonation tests may be required outside the half-cell test areas.

Although the battery of tests necessary to evaluate the concrete is outlined in the investigation proposal, language is typically included in the proposal to indicate to the owner that it may be necessary to perform additional tests after the initial results are obtained and reviewed.

The summary of the test data for our sample garage indicates that the deterioration did not extend much beyond that which was visible. Half-cell readings were low at locations away from deteriorated areas. The depth of chloride ion and carbonation contamination was moderate and had not reached the reinforcement level that was placed with proper cover. Delaminations and spalling were caused by low cover reinforcement at isolated areas and full depth cracking in the slab that allowed water and contaminants to access the steel directly. These areas can be taken care of with localized repairs. In cases where the contamination of the concrete has reached the level of the reinforcement, indicating that deterioration could accelerate in the future, then more extensive repairs may incorporate a waterproof membrane to prevent further contamination and water access.

Conclusions

Non-destructive testing of concrete structures yields valuable information for the engineer when investigating problems and can reveal unanticipated or hidden deterioration. The repair of the structure is guided by the results of the testing. The types of repair will vary by method and cost. In general, repairs need to protect both the undamaged and contaminated concrete elements from future deterioration. However, the structure will still experience some future corrosion, since any repair generally slows down the deterioration process but does not totally eliminate it. Discussion of the repair of concrete structures will appear in a future article in STRUCTURE® magazine.▪

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