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A Laboratory for Non Destructive Evaluation of Civil Structures

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Abstract

This paper describes the modifications made to the civil engineering materials laboratory course to include non destructive testing procedures. The materials course is required in the undergraduate program and taken at the junior level. The materials course as it was offered primarily covered the design and properties of Portland cement concrete, steel and asphaltic concrete. Additionally, testing for the properties of wood, plastics and aluminum was covered. The objective was to teach and conduct state-of-the-practice methods of obtaining virgin properties of materials which represents the basis of designing and constructing new structures.

The motivation behind the inclusion of non-destructive procedures in the materials laboratory was the urgent need for rehabilitating the nation's infrastructure. Civil engineers are responsible for the design, maintenance, inspection and operation of almost all public infrastructure such as transportation structures, water resources, water system structures and delivery structures, energy production and delivery systems, and building structures. An essential need today is in evaluating the safety, remaining service life, repair and rehabilitation of these structures in service.

The paper describes the non destructive procedures incorporated into the materials laboratory, namely:

- Eddy Current Procedure for mapping reinforcing bar topology in concrete structures.
- Hall effect sensors for mapping corrosion of reinforcing bars in concrete structures.
- Chloride Ion profiling for measuring the infiltration of deicing salt in concrete structures.
- Permeability measurement of concrete in service.
- Ultrasonic testing for defect identification in concrete and steel structures.
- Acoustic emission for monitoring of structures in service.

The paper also summarizes the student feedback on the changes made to the materials course.

Introduction

Non Destructive Testing (NDT) can be defined as being able to derive materials properties without having to damage the structure or the test specimen, or the use of destructive sampling methods. As these non destructive testing procedures become more prevalent in the engineering community it also is equally important that today's graduating engineers become familiar with these methods.

Throughout many of the country's urban areas, buildings, bridges, sanitary systems, and other infrastructure related systems have either reached or exceeded their expected design life. It is virtually impossible to economically repair or replace these systems at once. Engineers are currently rehabilitating the structures which are in the greatest need of repair largely using traditional structural assessment methods where structural information is collected primarily by inspection. Non destructive testing is a significant tool for documenting the structures' condition and allows the engineers to develop a more accurate estimation of a structure's strength thus providing a reliable estimate of the remaining service life. Proper use of NDT also allows planning engineers to repair those systems which pose the greatest risk to the community first, and make cosmetic repairs second.

In response to the issues described above a four phase plan was developed to expose the engineering students to the emerging NDT technologies. The first stage of the plan was to determine those NDT procedures which have the most potential use in civil engineering and could readily be adapted to classroom applications. The second step was to locate suppliers and determine the financial cost vs. teaching benefits. The third step was simply the acquisition and de-bugging of the equipment. The final step was to develop lab procedures which could easily be integrated into the current curriculum.

NDT is still considered an emerging field in civil engineering, thus it is difficult to determine the full impact of these procedures. However, on a smaller scale the success of these methods is indisputable. During the careers of the current generation of civil engineers NDT methods have the potential to become as common procedures. Six NDT procedures were selected as having the most potential: reinforcement location; corrosion mapping; chloride ion concentration profiles; ion permeability; ultrasonic testing; and acoustics emission testing. Pertinent information on these techniques is provided in the following sections.

Significance and Potential Uses of NDT Techniques in Civil Engineering

Mapping Rebar Topology: A major factor in the strength of a reinforced concrete member is the size and location of the reinforcement. When performing strength assessment, an engineer must know the size and locations of the reinforcements; this information mostly comes from the design drawings. In most cases for civil infrastructure as built plans are not available or are unreliable. The engineer must rely on experience and perhaps visual inspections. In either case an accurate strength evaluation cannot be performed. Visual inspections can be misleading and could yield results which may overestimate the structure's capacity. Traditional design methods tend to be overly conservative and can lead to an underestimation of the system's actual strength.

Currently there are NDT methodologies which can determine the size and location of the reinforcement within a concrete member in service. Rebar locator can also be used for quality control and quality assurance for assuring reliable implementation of the design drawings. Location of reinforcement must also be known if other structural components will be retrofitted into the existing structural member and connections existing rebars needs to be made. Currently the most prevalent use for this technology is to locate reinforcements before drilling anchorage holes into a concrete member. However, as our infrastructure continues to age, and retrofitting and upgrade projects increase in number and complexity, this technology is expected to become increasingly popular.

Corrosion Mapping: A major component of strength in a concrete member is the condition of the rebar. At early ages the properties of steel reinforcements are fairly uniform. However, as the structure ages, gauging the strength of a corroded reinforcing bar embedded in concrete becomes very difficult.

The most significant deterioration damage to reinforced concrete transportation structures is due to rebar corrosion. Once the corrosion of rebar initiates and is not remedied, the expansion of the volume of steel generates significant stresses which result in the expansion and cracking of the concrete component. The cracking damages the component and the loose cover exposes the rebars which leads to accelerated corrosion activity. Experts indicate that the average life of an exposed reinforced component without corrosion protection is five years. It is essential that the corrosion activity in rebars is regularly monitored in order to implement prevention schemes in order to extend the service life of exposed concrete structures. Corrosion mapping is a technique which allows the engineer to ascertain the locations and levels of corrosion activity without damage to the structure.

The effects of chloride ions on reinforced concrete structures are well documented in civil engineering. Corrosion is the result of the interaction of cations and anions in an electrolytic medium. In reinforced concrete structures the iron atoms in the steel act as the anions and free chloride ions from deicing salts provide the cations. These ions in the presence of moisture facilitate the corrosion of the reinforcements. The damage to the structure consists of two parts; a weakening of flexural capacity due to a reduction in uncorroded steel members, and loss of cover due to the expansion of the corroded member. Cover loss is a result of the pressure on to the surrounding concrete created by expansion of the corroding steel which can reach levels of 5000 psi. The loss of cover also expedites the infiltration of water which further corrodes and weakens structural components.

Chloride Ion Penetration Profiling: Chloride ion profiling can be used to assess the extent of chloride ion penetration into a structural system. This profile shows the amount of chloride ion concentration at various depths in concrete.

By knowing chloride ion concentrations within a structural system it is possible to make a number of engineering decisions pertaining to the condition of the structure. One such decision is the determination of the method of ion transfer from the exposed surface to the reinforcement system. By knowing the relative state of corrosion and the corrosion profile an engineer can determine the
time it took for the corrosive agent to reach the rebars, thus the life expectancy of the structure. The test procedure is extremely useful in determining the method or route of ion attack on

structural reinforcements. This technology nicely technique of determining chloride ion penetration complements other NDT procedures such as corrosion mapping and ion permeability. **Ion Permeability:** The relevance of determining ion permeability to structural assessment is that it helps clarify results from other NDT procedures such as corrosion mapping and ion concentration profiles. Once corrosion activity has been mapped and the profile has been established, by knowing the relative permeability of the concrete the exact ion transport mechanism can be identified and corrected. Ion permeability can also be used to estimate the remaining service life of a structure. For example, a bridge which appears to be in good condition may have been constructed using a highly permeable concrete, thus leaving the structure vulnerable to corrosion problems, which would significantly reduce the structure's service life. By being able to more accurately estimate the remaining service life, and using prudent preventative maintenance could dramatically reduce the repair/rehabilitation costs.

Ion permeability is traditionally measured using a ponding test. This test yields accurate values for the permeability of concrete but takes an extremely long period of time since it can only be run practically on a sample taken from a fresh batch of concrete. This lengthy test can be replaced with a semi-destructive ion permeability test which takes significantly less time. The term semi-destructive is used since a four inch diameter core from the structure must be removed. The ion permeability test does have one significant limitation; it will not give specific permeability values. The results obtained from this test are qualitative; a high or a low permeability. Further research needs to be performed in order to correlate the results of this type of experiment to actual permeability values in units of length per time.

Ultrasonic Procedures: Ultrasonic procedures are used with both reinforced concrete and steel structures. For accurate measurement of structural dimensions, such as thickness in areas where conventional methods may be difficult to implement or areas where access is available only on one side. Ultrasonic methods can also be used to detect a wide variety of internal flaws in structural systems. Relative density of materials can also be determined to ensure uniformity of materials on the job site or for use in mechanical property determinations.

The area of civil engineering most likely to be affected by ultrasonic technique is quality control and quality assurance. With the use of a few small sensors and a laptop computer, inspectors can perform numerous types of inspections in an accurate and economical fashion. Connections of structural components can be inspected for quality control; completed components can be checked for internal defects; and the uniformity of construction materials can be verified. Inspection is not the only civil engineering field to be affected by this technology. The ultrasonic methods used in inspection can be adapted to the assessment of structural systems as well, giving the engineer a wider data base from which to predict the strength of a structure and its remaining service life.

Acoustic Emissions Testing: Acoustic emissions techniques involve listening and recording the sound events generated by the structure during its response to a stimulus such as load, temperature, etc. These sound events or acoustic emissions can provide the engineer with data related to the stress distribution within the structure. The emissions can be classified into several categories. For instance, a fatigue crack may produce a very sharp spike, while yielding phenomenon can produce extended type wave patterns, which describe the mode of fracture, and through triangulation, the origin of the event can also be located when multiple sensors are used. By using these two pieces of data, or types of emission and location, it is possible for the user to locate areas of high stress and be able to identify the failure mechanism.

There are two potential uses for this technology in civil engineering. The most practical use is in the monitoring of structures under service loads. By placing sensors at key locations within a structural system, the engineer will be alerted to any areas of stress which may need to be accounted for. Another useful aspect of acoustic emissions is based on the fact that a structural component will only emit an acoustic signal from a specific location when it is stressed beyond the previous level of maximum stress. This fact allows an engineer determine the maximum level of stress the structure may have been subjected to over the course of its service life.

NDT Procedures in Civil Engineering Materials Laboratory

Mapping Rebar Topology: This NDT procedure is based on is Eddy currents. When a metallic specimen is subjected to a linear magnetic field through a coil, Eddy currents are induced in the specimen. The Eddy currents run in a direction opposite to the current direction in the sensor coil, and they will only form when there is a change in the magnetic flux, which is induced by alternating the current in the sensor. This phenomenon is also explained by Lenz's Law. Material properties, flaws and geometry affect the magnitude and phase of induced Eddy currents and thus can be identified by measuring the changes in the magnetic field parameters.

The intended use of this technology in the materials laboratory was the determination of internal geometric properties of reinforced concrete specifically the location and sizes of metal rebars. The students are first given a lecture on the basic principles and then are instructed on how to use the equipment. For the actual experiment itself two concrete test blocks containing several different sizes of reinforcing bars at various locations. The use of test blocks is to ensure that the apparatus is functioning properly and the student obtains accurate results

The laboratory test procedure involves three main steps. The first step is to use a sensor calibrated for both location and depth to locate the axis of all metallic components within the test block. A second sensor is then used to determine the diameter of the reinforcement bars. The final step is to use the locator\depth probe to determine the depth below the axis where the approximate center of the bar lies. The size of the bar must be known for an accurate depth measurement. The student is required to submit engineering drawings showing the size and location of the rebars. These results are compared to the original as built drawings to determine accuracy.

Mapping Rebar Corrosion Activity in Reinforced Concrete Members: This method is based on a phenomenon known as the Hall effect. When a conductor carrying a current is placed in a magnetic field, a voltage is generated in the direction perpendicular to both the current and the magnetic field. Corrosion mapping is done by measuring the voltage difference across the magnetic field surrounding the reinforcing members. Since, these members are uniform along the long axis one would expect a constant voltage difference along the same axis. However, as reinforcement corrodes they expand and the bar diameter will increase. This increase in diameter

is directly proportional to the increase in voltage potential differences. Thus, the corrosion measurement device allows the user to locate the areas of bars with increased diameters indicating the areas of high corrosion activity.
The purpose of this experiment was to give the students a method for quickly assessing the state of corrosion of a given structure. After the students are given a brief theoretical lecture they are asked to construct the corrosion map for a test sample. The corrosion map is a graphical representation of the areas on the test specimen which exhibits areas of high corrosion and is done by interfacing the mapping device to a PC. Two samples were tested using this procedure. One is made up of several blocks of reinforced concrete blocks that were kept indoors thus not subjected to de-icing salt and the second is a section of concrete slab, removed directly from underneath a de-icing salt container outside the Engineering Building on campus.

The test procedure consists of a number of steps. Since, a current must be introduced perpendicular to the magnetic field, at least one section of the reinforcement matrix must be exposed. This exposed section can be thought of as the positive terminal of the direct current. Next, the surface of the specimen is thoroughly wetted to ensure that the concrete will be able to conduct electricity. In completing the circuit the sensor that is placed on the surface of the specimen becomes the negative terminal. The direct current is supplied by the sensor itself, which is a half cell made up of a copper sulfate solution. Once the apparatus is set up the final step is to use the sensor to measure the potential voltages at various locations on the specimen. These voltages are then stored and displayed within the corrosion instrument. Students then can download the data to a spreadsheet program in a PC to further manipulate the data and generate graphical representations of the corrosion activity.

Chloride Ion Profiling: This method measures the amount of free chloride ions present in a concrete specimen. Free chloride ions in the concrete specimen are extracted by means of dissolving the concrete dust sample in a mixture of a mild acid and an oxidizing agent. Once the ions are dissolved in the solution, a voltmeter is used with a calibration guide to determine the percentage of chloride ions with respect to the mass of concrete sample. This procedure is repeated at various depths from the surface of the concrete member to develop the ion concentration profile.

The main objective was to give the students a tool with which they can assess the depth of chloride penetration and associated chloride concentration in a concrete structure. As with the

corrosion mapping no formal lecture time is devoted to the theory based on which the device operates. However, in the lab portion of the class the governing physical principles are outlined. The chloride ion profile is a graph which relates chloride ion concentrations to subsurface depth from which the sample was taken. For instructional purposes several concrete blocks were fabricated as control samples. The test samples were obtained from the same location as the samples used in the corrosion mapping procedure. Using samples of concrete (as opposed to on site experiments) was necessary due to limited laboratory hours and the unpredictability of outside weather conditions.

As with most NDT procedures the test is relatively short with a few steps. The first step is to prepare the probe and the display settings on the Rapid Chloride Test apparatus. In this step the display must show a value within the specified range to be considered accurate. If the measured value does not fall within the range the sensor must be cleaned and prepared again. Once the sensor is calibrated readings are taken from a mixture of the concrete sample and the extraction liquid previously mentioned. The readings from the test samples can then be compared to values in the calibration chart to determine the amount of free chloride ions present in the sample. The final step is to recalibrate the sensor to ensure that no damage occurred during testing.

Ion Permeability: This procedure is used to determine the rate at which ions that promote corrosion of rebars can penetrate concrete specimens. By measuring the concrete's ability to conduct electricity one can predict the ability to resist the penetration of chloride ions. That is the more electrical resistance the concrete has, the better it will be able to resist chloride ions.

The reason for developing this procedure was to complete the test series on reinforced concrete. Thus, not only can our students locate and size reinforcements but they can determine areas of high corrosion, the depth to which the chloride ions have penetrated, and the rate of chloride ion infiltration. Ion permeability is calculated indirectly by measuring the level of electrical charge that passed through the sample over time. The time to run this test is relatively short when compared to the traditional ponding test; about 30 hours, which is perhaps feasible for a commercial testing laboratory, but infeasible in a three hour educational laboratory session. Scheduling problems prevented us from fully implementing this test however, adequate time will be set aside for this procedure in the future.

The test procedure is delineated in AASHTO T 277-93. A four inch diameter of two inches must be extracted from the specimen. The side of the specimen needs to be coated with a non-conducting sealant. The sample is placed into a vacuum desiccator at a pressure of 1 mm Hg for three hours. Afterwards, the specimen is submerged in water without releasing the vacuum. This is done by using a seperatory funnel located directly over the specimen. The vacuum pressure is maintained for an additional hour. Next, the vacuum is released where the specimen remains submerged for an additional 16 to 20 hours. The sample is then secured in the test cell using a silicon based adhesive. One test cell is filled with a 3% NaCl solution and the other cell with 0.3 N NaOH solution. A direct current is applied to the load cell of 60.0 m +/- 0.1 V. The current is read and recorded every 30 minutes for a period of six hours. The current is converted into total coulombs passed over the test and related to a permeability rating.

Ultrasonic Testing: Ultrasonic test is used for a variety of purposes such as thickness measurements, flaw detection, and crack depth on both steel and concrete. Ultrasonic test generates a pulse or a stress wave through the test specimen. Information about the specimen is calculated by observing the time of flight attenuation and frequency characteristics of this wave. This is possible since ultrasonic wave velocity is affected by mass density, elastic and poison's ratio modulus. This is accomplished by utilizing a piezoelectric sensor which can either send a pulse by applying electric current or receive a pulse by transforming a pulse into a voltage. A computer software is available to determine the time it takes for the pulse to travel between sensors. From basic velocity relationships, material thickness can be computed. If the thickness is known, a constant time of flight should be present. Any variation in the time of flight is an indication of an internal defect or flaw.

The students are given a brief review of the physical properties of wave velocity in various media. They are then asked to use the ultrasonic set up to compute the thickness of several plates of unknown thickness and known material properties. From this simple test students are exposed to the theory and application of ultrasonic testing procedure.

The test procedure is fairly simple, starting with pulse parameters such as trigger levels, gain, damping, and amplitude of the pulse to be sent. The next step is to attach the sensors to the specimen by means of an acoustic couplant such as petroleum jelly. The internal pulser then sends a pulse through the material and is received by the second sensor. This is what is referred to as a through transmission test. For the pulse echo method only one sensor is used. This sensor sends out a pulse and waits for the pulse to return before sending a second pulse. Time of flight for pulse echo is twice the time of flight for a through transmission test. The data collected by the software is then displayed on the screen for storage or further analysis.

Acoustical Emissions (AE): Acoustic Emissions is based on the fact that as structures are stressed the material emits energy in the form of stress waves arising from microyielding or microfractures. Acoustic emissions technology lets the user listen to the events taking place within the structure under a stimulus. By using the theory that sound travels at different speeds, depending on the material, it is possible to locate the emission source. The main difficulty with acoustic emission is the number of events and the speed in which the events take place. However, these problems are easily overcome with the use of digital signal processors and a relatively fast data acquisition system.

The reason for including AE technology into the undergraduate materials laboratory was to familiarize them not only with AE but with data acquisition/analysis and (DSO) Digital Signal Processing software packages. Acoustical emission has several well documented procedures or applications. The most significant AE application is in structural monitoring. The second use is to determine the overloads on the structure. The building monitoring aspect of AE will be the

model used for instruction. By using loading equipment currently in the laboratory, students are given a structural member subjected to certain amount of stress and be expected to locate the areas under the most stress. Students are also expected to use the software to determine the type of emissions or type of material failure exhibited within the structure.

The execution of the test is simple and straight forward. The difficulty lies in setting up the test parameters, sampling rates, sensitivity, and any other relevant variables the user wishes to examine. The AE sensors are then attached to the test sample by means of a couplet, which allows for the stress wave to travel from the specimen to the sensor without any appreciable loss of signal. The AE tool utilized is the Mistras software developed by the Physical Acoustic Corporation which is designed to collect predetermined information. As the load is applied the sensors receive data until the experiment is terminated. The Mistras software records and processes this data.

Student Evaluations Of The NDT Laboratory

Several questions regarding NDT procedures implemented into the curriculum were posed to the students after the completion of the laboratory exercises. Questions were also directed to a group of students enrolled in the same course during the previous academic year, with no NDT coverage. Students were asked to respond based on a three point scale with one being the lowest value and three being the highest possible score. The results are presented in Table 1 and Table 2 for the two groups.

Table 1 - Questions posed to students exposed to NDT laboratories.

1. Do you feel that NDT techniques will benefit you in your career.

    1. No
    2. Possibly
    3. Definitely

Average response: 2.7

2. Was enough time given to the NDT procedures

    1. No
    2. More time was needed
    3. Yes

Average response: 2.2

3. What should be the next level of implementing NDT at Wayne State.

    1. Drop the subject altogether
    2. Retain same level of coverage.
    3. Create a separate course covering NDT

Average response: 2.6

Table 2 - Questions asked to students who completed the materials course with no NDT.

1. Would you be interested in a course dealing with Non Destructive Testing.

    1. No
    2. Possibly
    3. Definitely

Average response: 2.1

1. Do you feel that NDT would be beneficial to your professional career.

    1. No
    2. Possibly
    3. Definitely

Average response: 2.4

Based on the series presented in Tables 1 and 2 it can be concluded that both groups see merit in being exposed to NDT techniques believing it would benefit their careers. The group already exposed to NDT felt more time was needed to properly cover the subject, and favored the possibility of creating a separate course in NDT. Such a course has been developed at Wayne State University Civil and Environmental Engineering Department and is currently available as a technical elective to undergraduate as well as graduate students.

Summary and Future Plans

Non destructive testing procedures were integrated into the civil engineering materials course. Students were exposed to six new non destructive testing procedures which covered reinforcement location, corrosion mapping, chloride ion determination, concrete permeability, acoustic emissions, and ultrasonic testing techniques. Student evaluations indicated that inclusion of NDT procedures in the materials course is well received by them. Since time is insufficient to fully cover the topics in the lab portion of the undergraduate materials course, a separate course exclusively devoted to NDT is favored by the students.

We chose to implement the particular NDT procedures based on their potential impact on civil engineering applications. Based on the field application, testing procedures which help assess the condition of aging structural systems are selected as the NDT techniques for this implementation. Some of the procedures selected are standard procedures while others required a significantly larger expenditure in time and resources.

The standard procedures covered in the laboratory such as, the reinforcement location, corrosion mapping, and chloride ion concentration are ready to be moved out into the field. The ideal situation would be to take students into the field and ask them to collect various types of information about a structure using only non destructive procedures. This can be accomplished in an afternoon since these procedures can be run both quickly and efficiently with relatively little experience. Also by presenting three procedures in one or two lab sessions, more time can be devoted to more complicated non destructive testing procedures, such as acoustic emissions and ultrasonic testing.

Work is currently under way to improve the impact of both the acoustic emissions and ultrasonic laboratory procedures. As these laboratories can collect large amounts of data, it becomes a challenging task to give a student enough information in one or two sessions to fully understand the use of these procedures. We are continually working on developing laboratory experiments which are easily understood, while being able to illustrate as many facets of acoustic emissions or ultrasonic testing as possible. Ultrasonic procedures may, in the future, be presented in the context of flaw detection or a relative concrete property determination. Plans include the acquisition of additional channels for the acoustic emissions testing procedure, which will allow for more precise location of high stress areas and the monitoring of larger structures. To continue the advance in ultrasonic technologies a wider range of sensors must be made available as well as the acquisition of advanced digital signal processing software. The ultimate goal for both acoustic emissions testing and ultrasonic testing is to be able to implement these procedures in the field on actual structural components. It is our hope that this transition can be facilitated with the use of a high performance lap top computer using an extension box for the data acquisition cards.

Possible future additions to the NDT laboratory include implementation of new technologies. Some available new technologies would be worthwhile additions to the NDT laboratories are currently available. Holographic procedures allow for very precise measurements of deformations and vibrations which are almost impossible to measure with even some of the best ultrasonic equipment. Holographic capability could be achieved within a few months provided the necessary equipment is available. Digital photogrametry is also a possible addition to the laboratory. Digital photogrametry or tomography allows the user to create a scaled 3-D vector picture from two 2-D raster images. All of the system components required are readily available on the market, including the software algorithms for civil engineering applications.

The Civil and Environmental Engineering Department at Wayne State University currently has a fully functional non destructive testing laboratory offering several different test procedures to it students. As we continue to make improvements in the technologies it is our further goal to be a fully operational non destructive testing facility capable of performing a wide array testing and research in the laboratory and in the field.

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