

NONDESTRUCTIVE EVALUATION OF HISTORIC STRUCTURES

by

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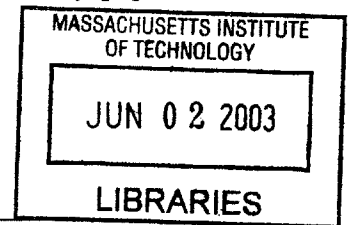
Submitted to the Department of Civil and Environmental Engineering
in Partial Fulfillment of the Requirement for the Degree of

MASTER OF ENGINEERING
In Civil and Environmental Engineering
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BARKER

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Abstract

This thesis is a requirement for the Master of Engineering (M.Eng) program in Civil and Environmental Engineering at the Massachusetts Institute of Technology.

An historic structure may need restoration because it is structurally deficient, does not meet current building codes, is in need of renovation, or is being subjected to different loads than those that were originally intended. It is typically less expensive to simply replace a structure than to restore it, so the decision to restore is usually based on the historical significance of that structure to the owner. Often, because of the age of the structure, the structural plans no longer exist, and even if they are available, there is no guarantee that the structure was actually constructed according to plan. In order to avoid further damaging the structure with destructive testing, engineers use nondestructive evaluation (NDE) to determine the location of key structural elements, locate defects or anomalies in a material, and to determine the quality of a material. Although NDE usually is best applied to homogeneous materials, such as steel, it can be successfully applied to heterogeneous materials, such as masonry and concrete. NDE techniques such as Impulse Response, Impulse-Echo, Infrared Thermography, and Ground Penetrating Radar have been particularly successful for concrete and masonry structures. These have been used on a variety of structures, including St. Peter's Basilica in the Vatican; Malpaga Castle in Bergamo, Italy; Tower of the Orologio in Venice, Italy; historic bridges throughout the United States; and the former Hong Kong and Shanghai Banking Corporation in Shanghai, China. It is important to note that NDE techniques must be carefully used in order to obtain an accurate understanding of a structure. A skilled technician should interpret all NDE results. Typically, more than one NDE test will be needed to obtain all of the necessary information to accurately evaluate a structure.

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LIST OF ABBREVIATIONS, ACRONYMS, AND INITIALISMS

ASCE	American Society of Civil Engineers
ASNT	American Society of Nondestructive Testing
GPR	Ground Penetrating Radar
F/T	Freeze/Thaw
HVAC	Heating, Ventilation, and Air-Conditioning
m	meters
MIT	Massachusetts Institute of Technology
mm	millimeters
MPa	Megapascals
NDE	Nondestructive Evaluation
NDT	Nondestructive Testing

1.0 INTRODUCTION

1.1 Purpose

This thesis is a requirement for the Master of Engineering (M.Eng) in Civil and Environmental Engineering program in High-performance Structures at the Massachusetts Institute of Technology. I have chosen the topic *Nondestructive Evaluation of Historic Structures* to provide some insight into this interesting area of study. In this thesis, I will be focusing on masonry and concrete construction materials. I have chosen to focus on these materials for the following reasons: (1) many historic structures are composed of these materials, and (2) concrete and masonry, being non-homogenous materials by nature, pose some of the most interesting and challenging problems to the nondestructive evaluation field.

1.2 Scope

In this paper, I will describe the application of nondestructive evaluation (NDE) techniques to historic structures. Because of the breadth of this topic, my paper will contain a brief description of a variety of NDE methods and their applications to historic structures. To further limit my topic, I will focus on the application of NDE to two specific materials, masonry and concrete.

1.3 Sequence of Discussion

In this thesis I will address issues concerning NDE of historic structures by first providing an introduction to the restoration of historic structures and NDE. I will then describe a variety of NDE techniques that may be used on concrete and masonry. Finally, I will provide some background information about masonry and concrete, and discuss several case studies.

2.0 NONDESTRUCTIVE EVALUATION AND HISTORIC STRUCTURES

2.1 Introduction

In order to discuss the topic of nondestructive evaluation of historic structures, it is first necessary to define what an historic structure is. For the purposes of this paper, a historic structure is a structure with historic significance, which is a definition that is clarified in the following quote:

Historic preservation has gained statutory acceptance at the national level through the National Historic Preservation Act of 1966 and through numerous state and local ordinances. During the time since the initial impetus for historic preservation, the accepted definitions of historic significance have been modified and reinterpreted as research has uncovered wider meanings and broader significance to the building activities of the past. For instance, although the term “historic bridge” may once have evoked images of covered timber bridges from the nineteenth century, or perhaps monumental structures such as the Brooklyn Bridge or the Golden Gate Bridge, research by historians, historic preservationists, and engineers has uncovered the significance of a much wider array of more ordinary projects, such as metal truss bridges (DeLoney, 1993). The research has identified the place of such structures in the history of transportation, industry, and technology... (Boothby and Rosson, 1998)

A national register criterion exists to help to define and classify historic properties. This criteria is available in *The Secretary of the Interior’s Standards and Guidelines for Archaeology and Historic Preservation* in *Federal Register* of 1983. The criteria are composed of the following four categories (quoted from Boothby and Rosson, 1998):

- Criterion A: Properties that are associated with events that have made a significant contribution to the broad patterns of our history.
- Criterion B: Properties that are associated with the lives of persons significant in our past.
- Criterion C: Properties that embody the distinctive characteristics of a type, period, or method of construction, that represent the work of a master, that possess high

artistic values, or that represent a significant and distinguishable entity whose components may lack individual distinction.

- Criterion D: Properties that have yielded, or may be likely to yield, information important in history or prehistory.

These criteria show that in addition to age, a building must have certain distinct properties that make it historic. These properties help to determine the value of the building to society, and the ultimate amount of money that may be used for restoration purposes. However, ultimately the amount of money that is put towards a restoration project is determined by the owner. Because the owner usually chooses to restore these structures because of their historic status, an engineer must be careful to address the historic preservation issues during restoration, avoid further damaging the structure, and provide finish materials that match the original design.

2.2 Restoration of Historic Structures

There are many reasons why an historic structure may need restoration. While it is a common school of thought that historic structures were better built than those of today, such often is not true.

Although it is generally thought that buildings were constructed more soundly in the past than they are today, such was not always the case. There are many examples of poor construction in even the most elegant and impressive old buildings, including mortar joints that were not completely filled, walls that were not tied together, joints between different materials that were not properly designed, and metal anchors that corroded easily. (Foulkes, 15).

An historic building may need restoration because it is structurally deficient, does not meet current building codes, is in need of renovation, or is being subjected to different loads than those that were originally intended.

Restoring historic structures can be a difficult and expensive task. Typically, it is more cost effective to simply replace these structures than to restore them. Because of the many uncertainties related to restoration, additional problems may be discovered during construction, which can lead to additional expenses. However, particularly in recent years, historians, architects, engineers, and the public have shown a growing concern for the state of historic structures, as shown by the National Historic Preservation Act of 1966. This movement for historic preservation has saved many historic landmarks that otherwise may have been destroyed. While the historic preservation movement has been visible in the United States, it is particularly evident in Europe. Europe has become a major research and application area for nondestructive evaluation, which can be attributed to the many historic and culturally significant buildings in need of repair throughout the continent.

2.3 NDE and Historic Structures

According to the American Society for Nondestructive Testing (ASNT), nondestructive testing (NDT) has been defined as “comprising those test methods used to examine an object, material or system without impairing its future usefulness” (ASNT 2002). The distinction between NDE and NDT is generally vague, and the terms are often used synonymously. However, NDT usually refers to the actual testing process, while “the word ‘evaluation’ has become increasingly associated with those methods for which quantitative interpretation of the test results is possible” (CNDE 2003).

There are many advantages to using NDE. One of the most important advantages is that the use of NDE prevents further destruction of a structure. If NDE is not used, a destructive testing method must be used, such as drilling or probing. These methods will certainly further damage the structure and hinder preservation, and may also disturb current stress-strain states.

Another advantage of NDE is that engineers can use it to determine how a structure was constructed, and to reliably determine the condition of a building. Often with historic structures, the original plans of the structure no longer exist, making it difficult for engineers to determine the structural design. Even if the plans do exist, many years ago construction teams were not subjected to the stricter building codes and construction regulations of today, so there is no guarantee that these structures were built according to plan. In addition, service and maintenance records for an historic structure are typically limited or do not exist. NDE can allow engineers to determine the structural make-up of a structure and allow them to locate key structural components, such as steel reinforcement. By using NDE, engineers can also determine which areas may be problematic through a general NDE survey, rather than through random coring. This can help limit the number of corings taken at structure to only problematic areas.

An advantage of NDE is that it allows engineers the freedom to test on the actual structure, as opposed to using a sample. Engineers can test in several locations and at multiple times (even continuously). While NDE can be an expensive alternative, it is one of the best ways to obtain detailed information about a structure.

3.0 NDE TECHNIQUES

3.1 Introduction

There are many different methods of NDE; however, many are best suited to homogeneous materials, such as steel. For concrete masonry structures, there are several methods that have proven successful despite the heterogeneous nature of these materials. These methods can be divided into several groups, including visual tests, thermography tests, stress wave tests, and ground penetrating radar (GPR). The methods discussed do not encompass every available method that may be applied to heterogeneous materials, but rather present some of the more successful methods that the author has found in her research. It is also important to note that typically a variety of testing methods must be applied to a subject to gain a sufficient understanding of the structure.

3.2 Visual Testing

One of the most basic forms of nondestructive testing is visual inspection. This method is self-explanatory, and involves carefully visually observing a structure. While this method usually cannot provide any in-depth data, it is extremely useful in helping to plan one's NDT program. A proper visual inspection may help an engineer decide where to perform a test and how to orient a testing device. An inspector should look for areas of damage or other deterioration, which may otherwise escape detection.

3.3 Infrared Thermography

Thermographic testing involves the use of infrared cameras to detect surface temperature distributions within an element. The infrared thermography equipment is able to sense radiation emitted by a wall, and then render that information into a thermal map based on a temperature scale. Except for the cost of the equipment, this method is fairly inexpensive and may be easily applied to large areas. One of the main uses of thermography in historic structures is for monitoring of moisture in masonry walls.

3.4 Stress Wave Tests

3.4.1 Introduction

Some of the most popular testing methods for heterogeneous materials involve stress wave tests. These tests include acoustic emission, impulse-echo, impulse response, and ultrasonic. Engineers can perform these tests either passively or actively. If they perform them passively, they do not add energy to the structure. If they perform them actively they do add energy, or a shock, to the structure. These methods involve a frequency analysis. Sonic tests are particularly useful for measuring thickness and finding voids. The main advantages of these tests are that they are easy to set up and inexpensive.

3.4.2 Acoustic Emission

In its simplest form, acoustic testing may be equated with listening to a structure with a very sensitive microphone. Acoustic Emission is typically a passive nondestructive test, so the inspector does not inflict any force on the object. Rapid energy releases within the subject cause mechanical vibrations, which in turn cause stress wave emissions. These energy releases are actually sounds that may be created by a variety of phenomena, including cracks that are forming

or propagating within the material; chemical reactions, such as corrosion; or dislocations, such as material breaking away from metal pins.

3.4.3 Impact-Echo

Engineers have had great success applying the Impact-Echo technique to heterogeneous materials, such as concrete and masonry. An Impact-Echo test is “based on monitoring the surface motion resulting from a short-duration mechanical impact” (Carino 2001). An engineer uses a testing device to apply a mechanical impact and then measure displacements close to the impact point. The impact generates shear waves (S-waves), surface or Raleigh waves (R-waves), and longitudinal waves (P-waves) (Figure 1). The longitudinal waves that travel into the specimen are reflected at discontinuities, defects, and at the back-face of the specimen. From the resulting waveforms, one can determine the depth (d) of these anomalies using Equation 1.

Equation 1

$$d = \frac{2\Delta t}{C_l}$$

Here, C_l is equal to the longitudinal wave speed of the specimen, and Δt is equal to the time between successive P-wave arrivals (Sadri 2003). Figure 2 shows a typical Impact-Echo test setup and results. Figure 3 shows an Impact-Echo test being performed on an actual specimen.

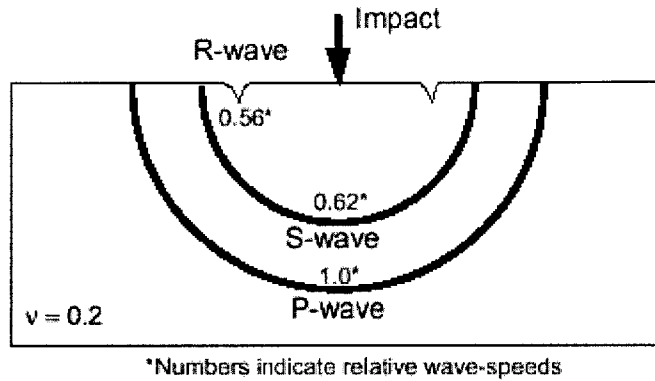


Figure 1. Impact-Echo testing produces longitudinal, shear, and surface waves. Source: Carino 2001.

Typical components of an Impact-Echo test include the following three items: (1) an impact source, (2) a receiver, and (3) a waveform analyzer. Engineers use the waveform analyzer to collect data, store waveforms, and perform the signal analysis.

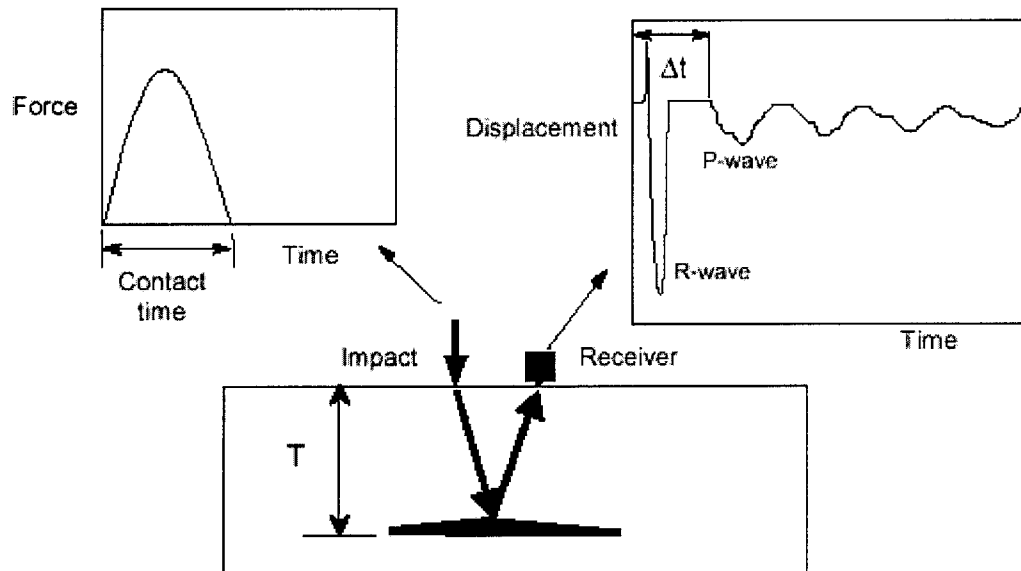


Figure 2. Impact-Echo technique. Source: Carino 2001.



Figure 3. Inspector performing Impact-Echo test. Source: Carino 2001.

3.4.4 Impulse Response

Impulse Response is one of the lesser-known NDT techniques. It is a stress wave test that is typically used on metallic elements in the aircraft industry. This method is related to the much better-known Impulse-Echo test, and uses “a low strain impact to send a stress wave through the tested element” (Davis et. al. 2001). Investigators typically use a 1-kg hammer that has a load cell built into the hammerhead. Investigators can then measure the response using a velocity transducer, or geophone. The stress levels created by the hammer vary by material, with levels of about 5 MPa for rubber tips to 50 MPa for aluminum tips. The compressive stress that develops at the impact location in the concrete can be related to the properties of the hammerhead material. Then hammerhead and the geophone can be connected to a portable computer in order to collect and store data (Davis et. al. 2001).

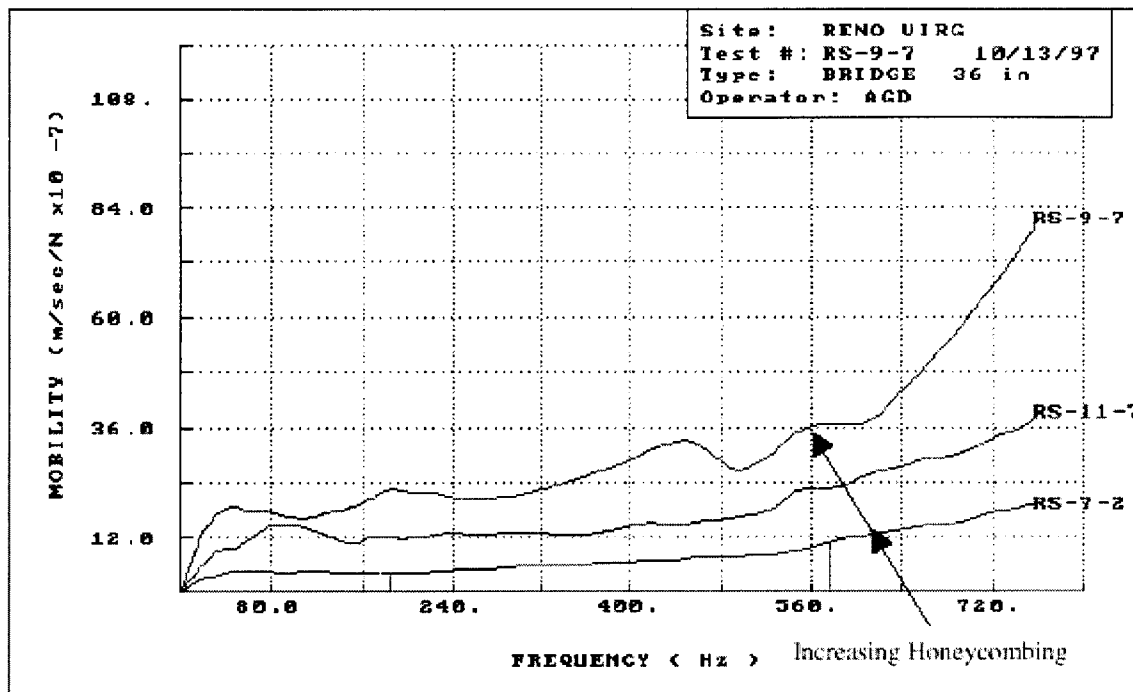


Figure 4. Typical results of Impulse Response testing. Source: Davis et. al. 2001.

The main difference between Impact-Echo and Impulse Response is described in the following:

When testing plate-like structures, the Impact-Echo method uses the reflected stress wave from the base of the concrete element or from some anomaly within the element (requiring a frequency range between 10 and 50 kHz). The [Impulse Response] test uses a compressive stress impact approximately 100 times that of the [Impact-Echo] test. This greater stress input means that the plate responds to the Impulse Response hammer impact in a bending mode over a very much lower frequency range (0-1 kHz for plate structures), as opposed to the reflective mode of the [Impact-Echo] test (Davis et. al. 2001).

In general, the difference between Impulse Response and Impact-Echo is that Impact-Echo uses much higher frequencies in order to detect small anomalies. Both tests use a fast fourier transform (FFT) algorithm to determine the amplitude spectrum.

Although not a well-known method, Impulse Response has been successfully used on a variety of civil engineering projects, such as detecting voids beneath concrete highways; detecting delaminations between steel reinforcement and concrete in slabs and walls; and detecting honeycombing and cracks in concrete. The test produces an output of average mobility.

If the average mobility remains constant, that concrete is sound; however, if the average mobility output peaks, then there is either poor consolidation or a delamination. Figure 4 shows a typical Impulse Response output. Impulse Response is a useful nondestructive test because it can provide reliable general information about a structure, such as locating areas of low-quality concrete, in a short amount of time.

3.4.5 Ultrasonic

Ultrasonic testing involves ultrasonic waves, which are waves at a high frequency (typically greater than 20,000 kHz). Ultrasonic tests have the best results when they are applied to objects that have a simple or uniform geometry and a smooth surface, such as steel plates. Typically, ultrasonic techniques do not work well on inhomogeneous materials, such as concrete and masonry. However, in recent years, researchers have made many advancements in the use of ultrasonic testing methods on concrete.

3.5 Ground Penetrating Radar

Ground Penetrating Radar is an NDE technique that has been used on historic structures, including those constructed of concrete or masonry. This technique has been used in civil engineering in a few applications, including measuring the thickness of road layers, locating substructures, and assessing reinforced-concrete ceilings in tunnels. However, while this method has great potential, it is still subject to limited use.

In GPR, a transmitter emits electromagnetic waves, which are reflected when they hit an anomaly. The propagation speed of a wave is dependent on the physical properties of the material that is being penetrated. Application of this method involves moving a transmitter/receiver antenna across a surface. The antenna may emit waves at a variety of

frequencies. A higher frequency (>500 MHz) will have poor penetration, but better spatial resolution than a lower frequency. A lower frequency will have a better depth of penetration than a higher frequency, but a poorer spatial resolution.

Although the applicability of GPR to determining concrete quality is still being studied, it is extremely useful for locating embedded structures, such as reinforcing bar, mesh, and utility pipes. GPR is easy to operate and can be performed quickly. It operates at a lower frequency than many other NDE methods, so it can have a deeper penetration, but will typically not produce as detailed results. For example, an engineer would be able to locate rebar in a structure, but would not be able to determine the diameter of the rebar. It is also difficult to interpret GPR readings at anchorages and overlaps.

4.0 MASONRY AND NDE

4.1 Introduction to Masonry and NDE

Many historic buildings are constructed of masonry. While masonry is a fairly durable material, it is still vulnerable to damage.

There are several special structural issues that one must consider when working with historic masonry. A masonry system involves brick or stone units joined together by mortar to form a wall. For many historic structures, the wall is part of the structural system. Therefore, the joints, and subsequently the mortar, are also part of the structural system. For this reason, the mortar must be able to take as much shear, compression, and tension loading as the masonry units. Masonry buildings also tend to have many projections. Projections need special structural support so that they can resist the overturning moment at the support and avoid deflection and failure.

A masonry building can experience damage for several reasons. It may be subject to improper design or site location, or poor construction techniques. The building may be subjected to loads that it was not designed to carry. It can be impacted by changes in the environment and in the surrounding area. A building may settle if the footings are not properly designed. Poor workmanship can result in an improper mortar mix, or masonry anchors not being installed.

In addition, many factors can cause masonry to deteriorate. Thermal effects can cause masonry to expand and contract. Typically, these thermal effects will not severely damage the structure unless the wall is composed of different materials that expand and contract at different rates.

The admittance of water into the structure can also cause damage. One of the main concerns with masonry is porosity, which is caused by voids in a building material. Water can enter a wall by the following five methods: (1) through the ground and rising by capillary action (rising damp), (2) at the base of the wall if the soil is not at the proper pitch, (3) through openings in the wall by rain and other water sources, such as air-conditioner condensation, (4) at the top of the wall through a breach in the roof, flashings, copings, or other permeable surfaces, and (5) through water vapor from inside the building that is drawn through the wall. Even if the pores are too small to hold water (otherwise known as micropores), they can still hold water vapor. It is important to recognize that water may act differently on a building now than when it was built because of changes to the walls, changes in heating and cooling systems, modifications to gutters, flashing, and drains, and insulation without proper vapor barriers (Foulks, 1998).

Once water has entered the building, it can harm the structure through several methods. One method is the expansion and contraction associated with the freeze/thaw (F/T) process. Water can also carry dissolved salt from its original location on the brick or mortar and into the pores. The salt then crystallizes, and the new crystals are larger than the original dissolved salts, putting pressure on the pores. The interaction between the water and the salt can lead to subflorescence and efflorescence.

Biological organisms can also play a major role in the deterioration of masonry walls. If algae, fungi, lichens, mosses, or bacteria are visible on a wall, it is a sign that there is too much water on the wall. Usually these organisms only cause superficial damage; however, there are some types of bacteria that hold moisture in the wall, causing additional damage.

Larger organisms, such as trees and vines, can also stimulate decay of a masonry wall. Tree roots can grow to break foundations or displace soil under footings. Many vines have small

tendrils that grow directly into the wall, causing damage. Trees and other plant-life tend to block sunlight on the wall, prohibiting the drying of moisture. Vine coverings make inspection of a wall more difficult.

4.2 Case Studies

4.2.1 Introduction

Engineers have successfully applied NDE to a variety of historic masonry structures. In the following case studies, I will describe three buildings that engineers have performed NDE on. These buildings are the Tower of the Orologio, Malpaga Castle, and St. Peter's Basilica. I obtained most of the information about these buildings from the proceedings of the *15th World Conference on Nondestructive Testing*, which was held in Rome, Italy, in the year 2000. The articles were *Nondestructive Investigations for the Safeguard of the Tower of the Orologio, in San Marco Square in Venice*, by Dario Almesberger, Antonio Rizzo, Sergio Meriani, and Raffaella Geometrante; *Analysis of Moisture for the Preservation of Frescoes at Malpaga Castle*, by Elisabetta Rosina and Guido Roche; and *Ground Penetrating Radar Applications on the Façade of St. Peter's Basilica in the Vatican*, by Giuseppe Giunta and Giuseppe Calloni.

4.2.2 Tower of the Orologio

The Torre dell' Orologio, or clock tower, is located in San Marco, Venice (Figure 5). The clock for the tower was complete in 1495, and the tower was completed approximately 2 years later. In 1500 the Senate decided to add buildings to either side of the tower, which were completed in 1506. In 1755, 8 columns were added to "reinforce the pillars at the ground level and support the two lateral bodies" (Almesberger et. al. 2000). The building helps to link the piazza to the rest of Venice and is a subsequently a major civil and religious symbol in Italy.

From a visual inspection, it is clear the building is in need of restoration. One can see that there is a major crack along the keystone of the arcade, there are cracks on the arch imposts, and there are cracks on the limestone slabs. There are cracks on the ground floor pillars, which are coupled with signs of crushing. Investigators were also concerned about possible deformations in the vault where the clock is because of thermal effects from a nearby glassworks oven. Inspectors used a combination of magnetromic, endoscopic, sonic, and ultrasonic techniques to nondestructively evaluate this structure.



Figure 5. Tower of the Orologio. Source: Almesberger et. al. 2000.

From the magnetromic investigation, inspectors were able to locate metallic elements in the structure. Magnetromic surveys are useful for locating metallic elements, although other methods are usually employed to determine detailed geometry of the elements. During the inspection, investigators used two different probes, a standard 100 mm probe, and an advanced 220 mm probe. In addition to some other metallic elements, investigators located an unknown metal plate, which they were able to attribute to the cause of some slab cracking. As the plate corroded, it expanded, causing the slab to crack.

The investigators found that the endoscopic investigation was one of the most useful for obtaining information about walls, including thicknesses, cavities, and binders. Endoscopic investigation involves real-time imaging of the inside of structure with the aid of a miniature camera (Figure 6). However, this method does require the presence of a bore hole. On the Tower of the Orologio, whenever possible, investigators took advantage of boreholes that were present from previous explorations. The camera was inserted into the 14 mm boreholes to a depth of 500 mm. From the endoscopic investigation, inspectors realized that mortar was degrading in some areas.

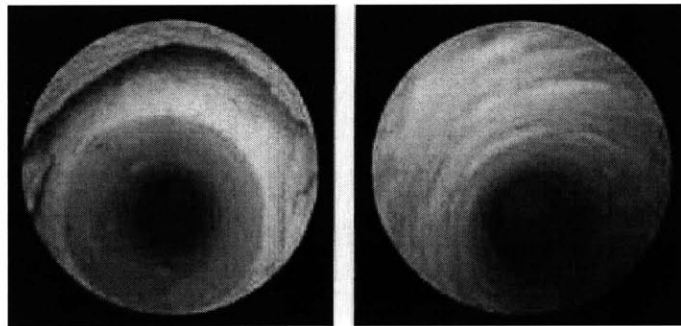


Figure 6. Photos from the endoscopic investigation of the Tower of the Orologio. Source: Almesberger et. al. 2000.

From the sonic investigation, NDE technicians were able to locate some detachments of facing stone slabs from the brick masonry. High velocities obtained from the ultrasonic tests on the ground floor pillars revealed that the stone was overloaded. Sample results from the sonic and ultrasonic investigations are shown in Figures 7 and 8, respectively.

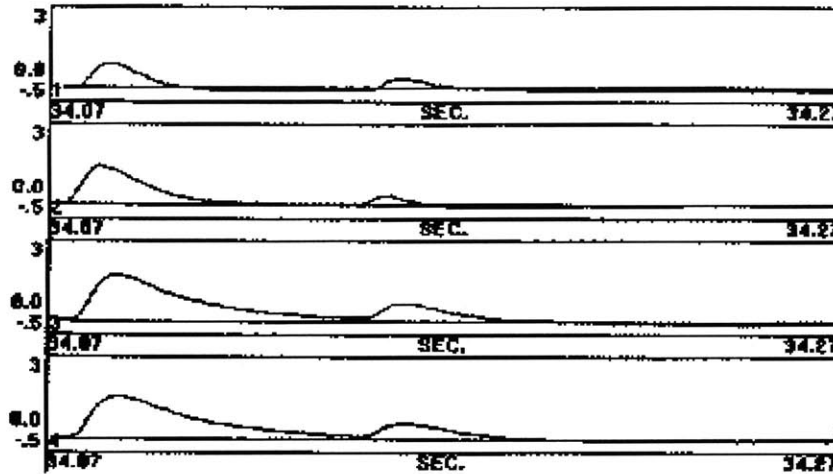


Figure 7. Results of sonic investigation. Source: Almesberger et. al. 2000.

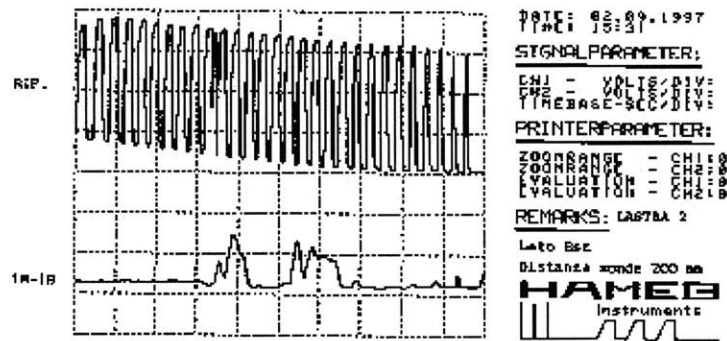


Figure 8. Results of ultrasonic investigation. Source: Almesberger et. al. 2000.

4.2.3 Malpaga Castle

Malpaga Castle is located in Bergamo, Northern Italy (Figure 9). Construction began on the castle in the 14th century, and was completed in the 15th century. Some of the unique features of the castle are frescoes painted on the castle walls. The castle has 3 layers of frescoes that have been painted over each other over time. The castle is going to be taken over by the Accademia Carrara Exhibition, and will be undergoing some renovations, including the installation of a

Heating, Ventilation, and Air-Conditioning (HVAC) system. Investigators have carefully used NDE techniques to determine the condition of the masonry walls and frescoes in the castle, and to help determine the best layout for the Exhibition without further damaging the frescoes. Only NDE could be used because of the precious nature of the frescoes.

Masonry and frescoes tend to be very sensitive to moisture, so the use of the rooms and the location of the planned HVAC system had to be carefully studied in order to avoid damaging the paintings. Many of the walls and frescoes have already been damaged by moisture. While this damage is visible, an investigator cannot determine the depth of deterioration, which may be anywhere from a few millimeters to 10 cm, without other NDE techniques.

In order to determine the best placement of the system, an engineer should have a precise knowledge of masonry building methods, climactic conditions in the room, and moisture levels in the room.



Figure 9. Malpaga Castle, front view. Source: Rosina et. al. 2000.

Malpaga castle has been troubled with moisture problems for centuries. The building suffers from a poor design that leads to water infiltration, and the ancient walls are highly porous to liquid and water vapor. The walls are also subject to water infiltration by damp rising, or

capillary action. These problems become even more severe when coupled with the freeze/thaw cycle of water in the walls.

NDE investigators used infrared thermography to monitor moisture in the walls and to locate delaminations of plaster and masonry bonds, and to locate infilled openings. Through thermography, they were able to locate areas of damage and areas that posed risks for future damage. Figure 10 shows a castle wall, and Figure 11 shows a thermographic imaging of that wall.

Investigators also installed sensors to monitor temperature and humidity in the castle daily. The masonry in the castle is quite thick, ranging from 60 to 80 cm in depth. Investigators determined that in many rooms, a combination of poor ventilation and cool temperatures was causing condensation on the walls.

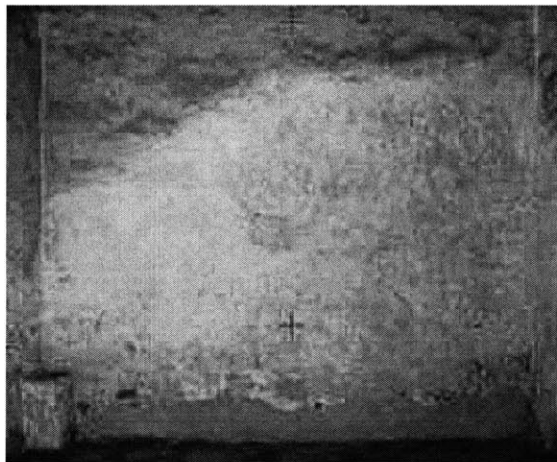


Figure 10. Wall in the castle. Source: Rosina et. al. 2000.

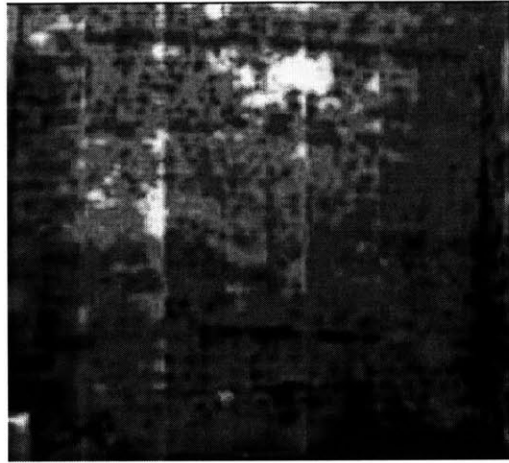


Figure 11. Thermography results of wall inspection. Source: Rosina et. al. 2000.

From their careful studies, the investigators on this project were able to determine the causes and extent of water infiltration in the castle, and to subsequently remedy these issues (Figure 12). They were also able to design a renovation plan that would not harm the masonry walls or frescoes, including choosing locations for various types of spaces, such as meeting rooms, hallways, and cafeterias, and to design the HVAC system.

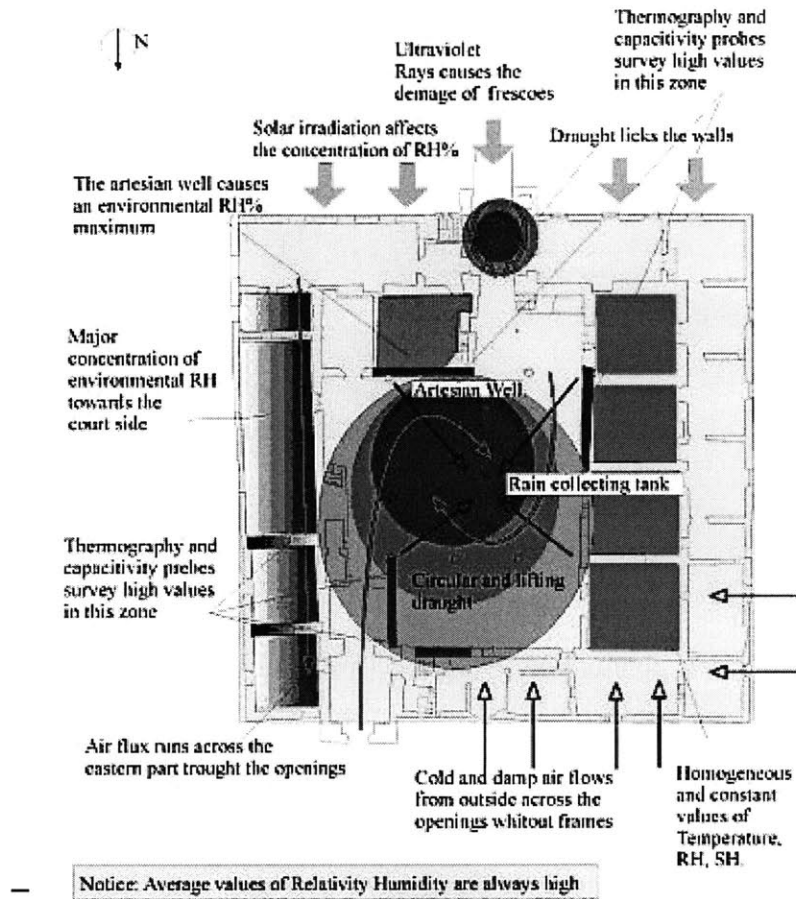


Figure 12. Malpage Castle, design solutions. Source:

4.2.4 St. Peter's Basilica

St. Peter's Basilica is located in the Vatican (Figure 13). It was originally built in 1546, and has been undergoing restoration for the past several years. During the NDE analysis, inspectors focused much of their attention on architectural features of the façade, such as the columns, pilasters, and clocks. They also studied cracked zones that had formed in the façade.



Figure 13. St. Peter's Basilica

The NDE inspectors predominantly used a combination of photogrammetry and ground penetrating radar. By integrating photogrammetric data with GPR survey results, they were able to map approximately 4000 sq. m. of the 7000 -sq.-m. façade (Figure 14). Investigators were also able to use special software to import their GPR and photogrammetric data into an AutoCAD program, creating 3D models of their results.

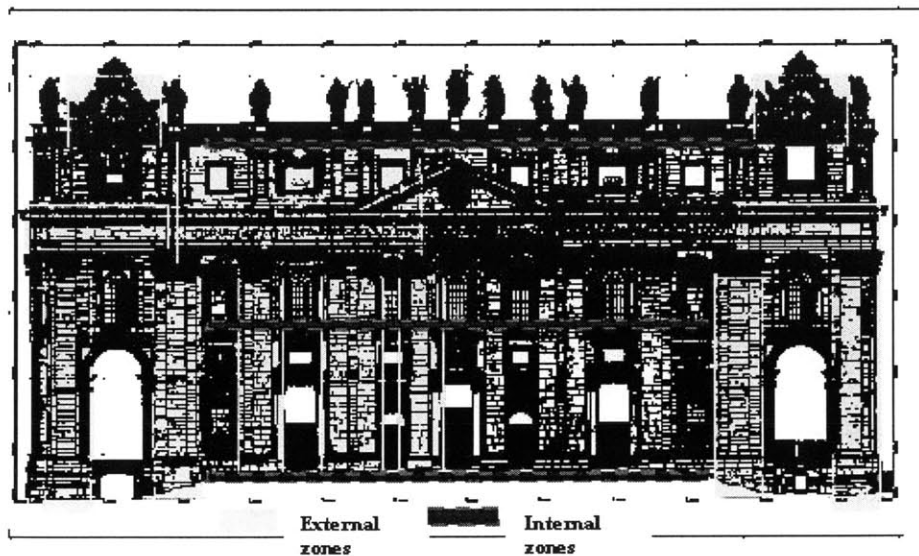


Figure 14. Map of façade from photogrammatry data imported into CAD. Source: Giunta et. al. 2000.

By using GPR analysis, the investigators of St. Peter's were able to determine information about the internal structure of the façade, including detailed information on the “travertine stone facing, masonry structure, plugs, cramp irons, cavities, [and] detachments” (Giunta et. al. 2000). This information would have otherwise had to have been obtained through a destructive analysis. Figure 15 shows an investigator performing GPR tests.



Figure 15. Inspector performing NDT tests. Source: Giunta et. al. 2000.

Investigators operated the GPR survey at several different frequencies in order to study different depths, which varied from 50 cm to 3 m. For the majority of the study, they ran the tests at 900 MHz. However, they also performed tests at 1.5 GHz to obtain a 70 cm penetration on the clocks, and at 200 MHz to study 10–12 m depths at the portico. The inspectors typically ran their tests at a rate of 1 m per minute.

There are 4 columns on the façade. Each column is cylindrical with an average diameter of 2.5 m. The NDE inspectors applied GPR on the column surface along 3 vertical lines, which were oriented at 0, 90, and 180 degrees with respect to the plane of the façade (Figure 16). They

scanned at 900 MHz for a depth of 1.3 m. They were able to survey 18 m of the 22-m-tall columns. Figure 17 shows some results from the column investigation.

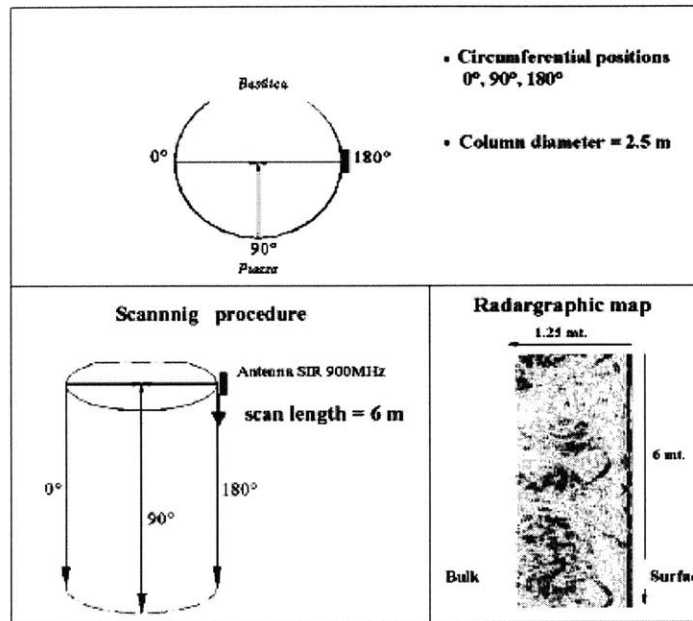


Figure 16. Scanning procedure for columns. Source: Giunta et. al. 2000.

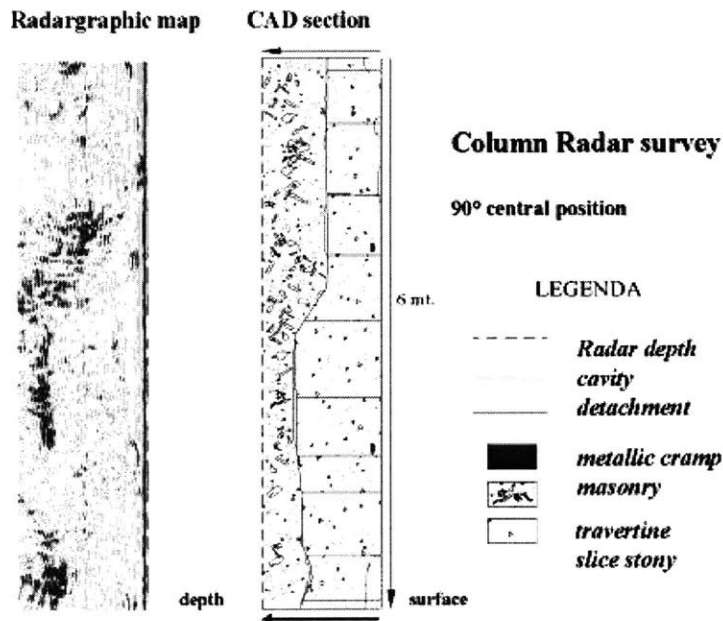


Figure 17. Results and interpretation of column testing. Source: Giunta et. al. 2000.

There are also 4 pilasters located on the façade. Inspectors moved the antenna horizontally around the 3 sides of the pilasters, and then vertically in steps of 20 cm (Figure 18). With this method, they completed approximately 130 sections for each pilaster.

For the pilasters and columns, inspectors were able to use GPR to obtain accurate geometry and material composition. They found some detachment of the stone and masonry, and were able to locate metal cramps, which indicated where blocks had been fixed.

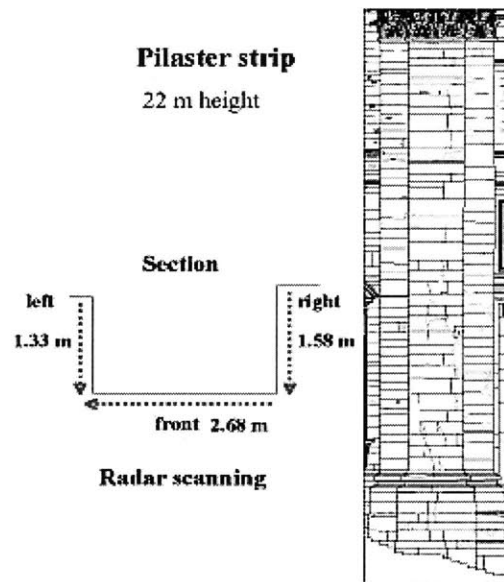


Figure 18. Scanning procedure for pilasters. Source: Giunta et. al. 2000.

Two clocks are located on the façade of the basilica. The clocks are affectionately named Oltramontano and Italiano. On the clocks, inspectors integrated GPR, photogrammetry, and thermography, and obtained results on the order of a few centimeters. From these tests, they located the following three layers of material: mosaic (1.5–2.0 cm thick), mortar (1.5–2.0 cm thick), and peperino stone (40–42 cm thick). Although Italiano proved to have survived the past

few centuries with minimal damage, the tests did show significant detachment of the mosaic from the mortar on Oltramontano. A summary of the test results is shown in Figure 19.

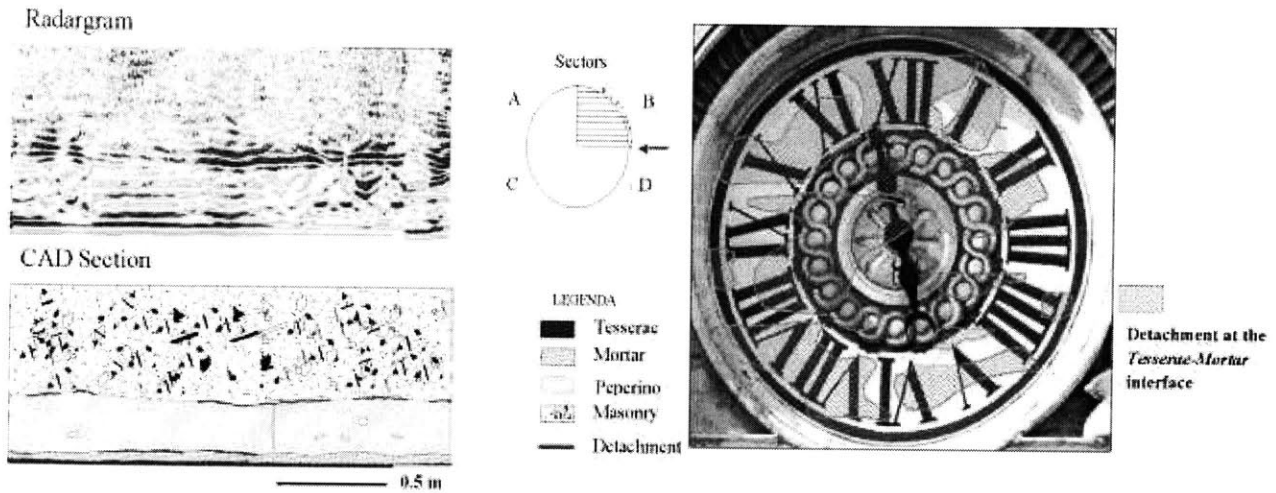


Figure 16. Radargram, CAD Section, and Plan View of Detachment of Oltramontano. Source: Giunta et. al. 2000.

Part of the NDE analysis included an inspection of the cracked zones on the façade. There are four main, vertical cracks on the left side of the façade, which have been visible since the basilica was constructed. The cracks are usually attributed to settlement related to poor soil conditions on that side of the façade. Inspectors ran a radar survey from which they were able to determine the exact size of the cracks, including their superficial and internal width (Figure 20).

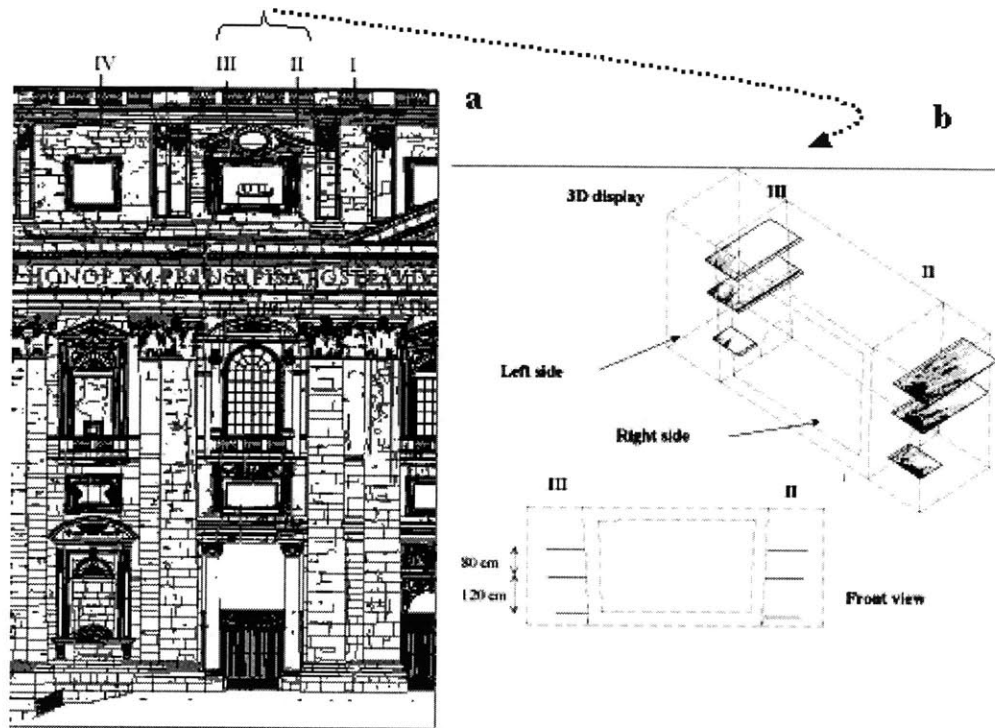


Figure 17. Mapping of crack inspection results and interpretation of data. Source: Giunta et. al. 2000.

5.0 CONCRETE

5.1 Introduction to Concrete and NDE

Many concrete structures, both historic and recent, are in need of NDE. An historic concrete structure may be damaged for a variety of reasons.

Concrete may be internally damaged in many ways, including damage from freeze-thaw (F/T) expansion, alkali-aggregate reactions (AAR), and internal cracking by mechanical loading.

Moisture is one of the most severe problems with concrete. Externally, exposure to weather, such as rain, sleet, wind, and snow, can cause concrete surfaces to weather and erode. Internally, water can become trapped in concrete in several ways, although the most troublesome is “free water” that becomes trapped in larger pores. During the F/T cycle, water in these pores freezes, which causes pressure by expansion. The pressure may cause cracking or surface scaling or spalling. One of the main ways to combat F/T damage is by using air-entrained concrete. The resistance of concrete to F/T has been directly related to the percentage of entrained air, up to 6–8%. However, air entrained concrete is a relatively recent development, and was not available for older structures; so, older structures are particularly susceptible to F/T damage.

AARs are chemical reactions between cement and aggregate minerals. Typically, the reaction occurs between the alkali in the cement and either silica or carbonate in the aggregate. The damage that occurs is similar to F/T damage, but may take 5–10 years to manifest.

In addition, any biological material that resides on concrete can hold moisture into the surface. Biological materials that infiltrate a crack may expand and cause additional damage. Biological growth may create chemical by-products that deteriorate cement.

A concrete structure may also have problems associated with poor workmanship or poor-quality materials. Many of these problems can be attributed to a limited knowledge of concrete and its chemical behavior during early construction projects. Construction crews and engineers of earlier eras did not yet fully understand how a concrete structure could be affected by creep strains or thermal expansion and contraction. Subsequently, few historic concrete structures were properly outfitted with expansion joints, although they are common today (Foulkes 1997).

Early construction crews and engineers also typically did not understand the affect of grading concrete, and instead used a one-sized grading distribution. This distribution leads to poor consolidation of the concrete, making it weaker and difficult to place around steel reinforcement (Foulkes 1997). They also did not understand the need for consolidation. Concrete should be vibrated to avoid void spaces where there is aggregate but not cement paste, a condition known as honeycombing. Because early workers did not know about the importance of consolidation, many historic structures have honeycombing problems.

In addition, there are many problems that affect both historic and contemporary concrete construction. Cold joints, which are created when concrete is placed in thin layers, so that one layer is placed upon an already hardened layer, are still a common problem. Improper mixing techniques, such as adding impure water or using an incorrect water-to-cement ratio, can inhibit the strength and durability of concrete. Other potential problems include insufficient cover, which can allow water to penetrate to the steel and cause it to corrode. Improper curing techniques can cause reduced strength and shrinkage cracks. Delaminations are another problem, which can occur for a variety of reasons.

A poor structural design may also cause a concrete structure to deteriorate. For example, improper concrete strengths and improper bar sizing and spacing may cause a concrete structure

to deflect. If expansion joints are not included or properly placed, a structure will probably crack under thermal stresses.

As with any structure, proper maintenance is a key factor in limiting deterioration. Cracks should be filled in quickly to prevent water infiltration. Exposing concrete to chemicals, such as road salts and other de-icing materials, can cause deterioration of both concrete and steel reinforcement, which is particularly applicable to structures such as bridges.

5.2 Case Studies

5.2.1 Introduction

The Romans invented concrete in ancient times. However, up until the 1880s when equipment advancements made cement and steel reinforcement increasingly more affordable and of better quality, concrete was rarely used as a building material. Most likely, this is because concrete was typically viewed as an engineering material rather than an architectural material (Foulkes 1997). For this reason, in the case studies in this section, I will predominantly present bridges, which were commonly considered an “engineering” project and thus suitable for concrete construction. However, I will also present one building, the former Hong Kong and Shanghai Bank.

5.2.2 Historic Reinforced Concrete Bridges

5.2.2.1 Introduction

Some of the most common concrete structures exposed to NDE are reinforced concrete bridges. Engineers at Construction Technology Laboratories, Inc., studied seven historic concrete bridges that had been constructed between the years 1907 and 1938. The company performed field

investigations, which included a visual inspection, Impulse Response, Impact-Echo, ultrasonic pulse velocity, impulse radar, covermeter, and corrosion testing. In particular, impulse response proved to be a very useful test on these bridges. The discussion of four of the seven bridges is based on the paper *Evaluation of Historic Reinforced Concrete Bridges*, by Allen G. Davis, Carlton A. Olson, and Kevin A. Michols. The paper was a published conference proceeding for a “Structural Engineering Odyssey,” a part of the American Society of Civil Engineers 2001 *Structures Conference and Exposition*.

In general, there are three main reasons why an historic bridge would require structural evaluation. The first is an increased interest in history and historic preservation, as discussed in Section 2 of this paper. The second reason is related to safety issues, which include adjusting lane widths and modifying approach alignments to meet current requirements. The third is very common, and addresses the need to check the behavior of the structure under adjusted loading conditions (Davis et. al. 2001). Most historic bridges were not designed for the heavy vehicular traffic of today, and are therefore in need of upgrading. The following case studies show how NDE can be applied to historic bridges in order to obtain information about their structural condition. The engineers’ objective for using NDE was to determine which areas of the bridges were problematic and required further analysis, and, in some cases, to determine structural properties.

5.2.2.2 Reno, Nevada

The Reno, Nevada, bridge that engineers from Construction Technology Laboratories studied was a double spandrel arch bridge. The bridge was constructed in 1907 and has arches that are approximately 25 m long and 25 m wide. The engineers were only able to obtain a limited amount of historical records on the construction of this bridge. From the information that they

were able to obtain, it seemed that the arches were approximately 1.5 m thick at the spring line, and decrease to 0.6 m thick at the soffit. The arches were infilled with soil to create a subgrade for a flexible deck.

From a visual inspection, engineers were able to determine that concrete piers were placed at 0.3 m lifts using wooden forms. The arches were built using 3-m-wide wooden lifts at 1.2 m above the water line. The investigators noted spalling on the underside of the bridge, particularly at construction joints and along the water line. They could also see some exposed steel reinforcement in the arches that appeared to be 25-mm² bars that were deformed.

Inspectors first used the Impulse Response technique to locate areas of varying concrete quality, such as poor consolidation and delamination of the concrete and steel. They used a 1.5 m x 1.5 m test grid under each arch. They accessed this position with the aid of a snooper truck positioned on the bridge deck (Figure 21). In plate-like structures, such as slabs, walls, and decks, sound concrete will show a constant average mobility in the Impulse Response test. When concrete is poorly consolidated, or honeycombed, the Impulse Response results will show an increase in average mobility and a reduction in dynamic stiffness. If delaminations are present, the Impulse Response will show a dramatic increase in average mobility and a substantial reduction in dynamic stiffness.

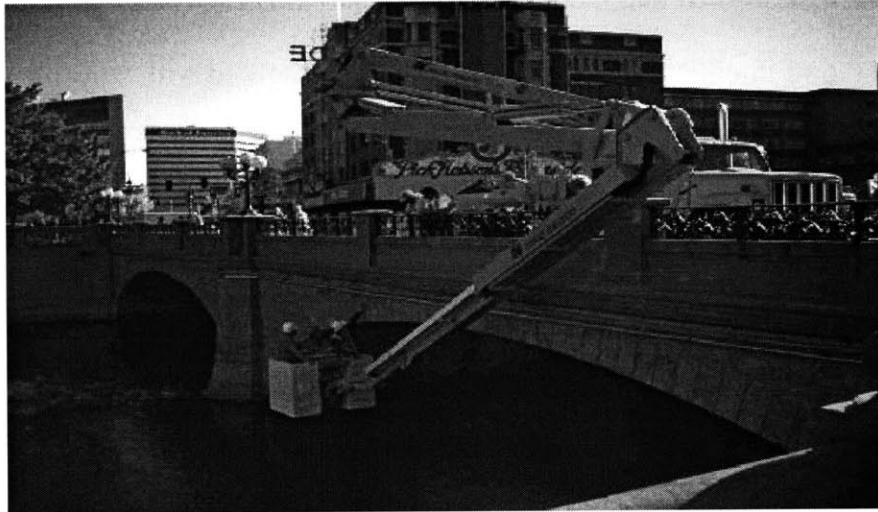


Figure 18. Snooper truck used at bridge in Reno, Nevada. Source: Davis et. al. 2001.

Engineers used Impulse-Echo to reanalyze problematic areas that the Impulse Response test revealed. The Impulse-Echo test provides more detailed data, such as concrete thickness and depth to anomalies. The results of the Impact-Echo test helped engineers to determine where any cores would need to be taken. Investigators later analyzed these corings to validate the NDE results, and to check chemical and physical properties, such as chloride content, alkali-silica reactions, and F/T damage.

Engineers also performed direct transmission stress wave tests on the central pier noses. From the results of these tests, engineers could determine material properties of the concrete, such as the compression wave velocity.

5.2.2.3 Cumberland, Rhode Island

Engineers studied an historic bridge in Cumberland, Rhode Island, that consisted of two approach spans and five arched spans. The bridge was predominantly cast-in-place, reinforced

concrete, and was constructed between 1934 and 1936. The center span of the arch is approximately 18-m tall and spans 48 m.

From a visual inspection, engineers were able to determine that the bridge deck was too deteriorated to salvage (Figure 22). They also noted low quality concrete on the center span arches. Throughout the restoration process, the engineers found unexpected areas of additional damage. They found that some parts of the bridge had been removed for patching, however, some areas had been filled in while others had not. Investigators used NDE to locate and determine the extent of cracking, delaminations, F/T deterioration, and areas of poor consolidation.



Figure 19. Cumberland, Rhode Island bridge with deck removed. Source: Davis et. al. 2001.

Engineers mainly used Impulse Response testing on this bridge. Engineers used the results of the Impulse Response test to determine which areas needed further investigation. They

then applied Impulse Echo to these areas to confirm the Impulse Response results and to obtain more detailed information, such as the depth and extent of the anomalies.

The investigators used a 1 m² grid, resulting in 53 North-South test columns and 4 East-West test rows. For Impulse Response, average mobility values for sound concrete are typically less than 3, so engineers used Impact-Echo on any area that had an Impulse Response value greater than 3. Figure 23 shows an inspector performing an Impact-Echo test.

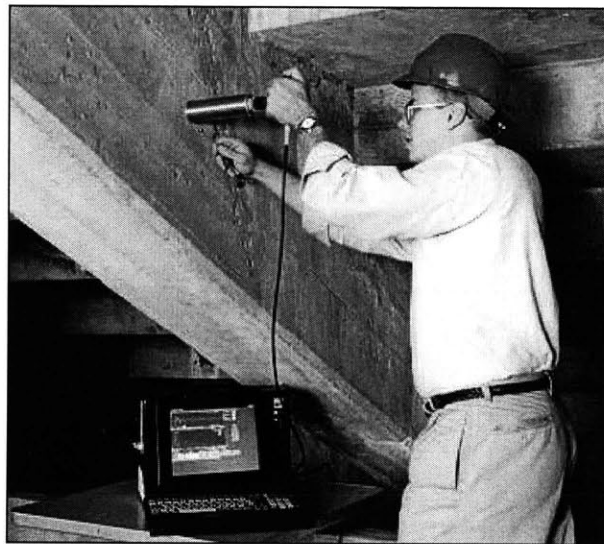


Figure 20. Worker performing Impact-Echo test. Source: Carino 2001.

Ultimately, the engineers found a few areas of poor consolidation. They did not find any areas that produced a sharp rise in Impulse Response average mobility, which would indicate cracking or delaminations.

5.2.2.4 Tacoma, Washington

This historic bridge is an open-spandrel, four-arch bridge and was built in 1925. The deck is reinforced concrete and 120-m long. It has a 25-mm thick asphalt overlay. The deck was cast with transverse beams at 3-m spacing that cross the 4 arch spans. Three transverse expansion

joints are located at 9 m, 60 m, and 111 m from the South end of the deck. Two sets of steel tram rails are still present on the deck. Visually, the deck and asphalt appeared to be in good condition.

From a visual inspection, inspectors noted insufficient cover on some of the arch columns. Covermeter measurements revealed that on one column, on one side the cover was less than 12 mm, while on the other side it was approximately 90 mm. The inspectors attributed this to a tall, slender steel reinforcement cage that had leaned to one side in the column formwork.

Engineers first used Impulse Response to determine the quality of the concrete in the deck. One advantage to using Impulse Response for this test is that it can penetrate a limited thickness of asphalt (up to a maximum of about 50 mm). However, the temperature must be low enough to maintain the stiffness of the asphalt.

Engineers used 2 test rows at 1.5-m intervals along the bridge deck. They found that all of the average mobility values were below critical, indicating that there were no delaminations. They also found that only one test point showed any signs of deterioration.

5.2.2.5 Putnam County, Indiana

The historic bridge studied in Putnam County, Indiana, consists of an open spandrel, single arch. It was built in 1929. The bridge has 2 short approaches and a 39-m span, with a width of 5.5 m (Figure 24).

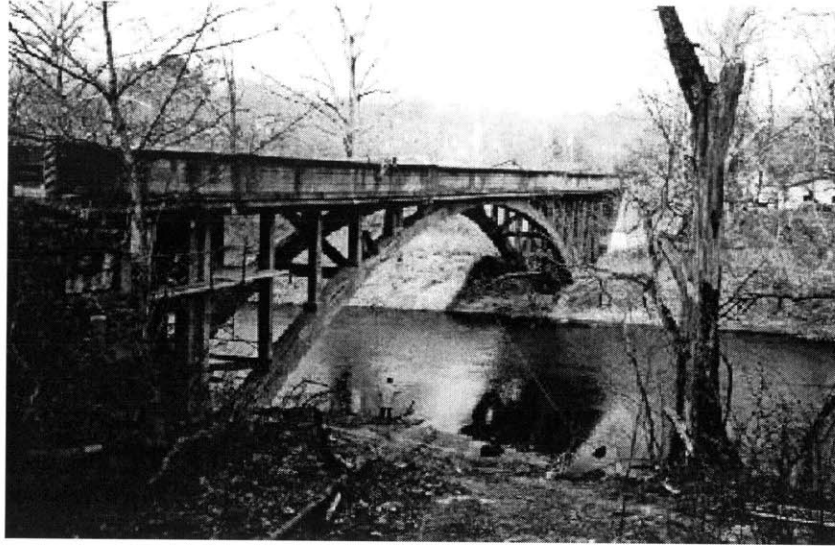


Figure 21. Putnam County Bridge. Source: Davis et. al. 2001.

From a visual inspection, engineers thought that the bridge appeared to be in poor condition. However, when they used Impulse Response testing along both arch beams, they determined that the concrete was actually sound with good consolidation and minimal cracking. They determined that the visible damage was caused by water flowing through the expansion joints and onto the arches. This water drainage caused some F/T damage in the cover and some corrosion of the steel reinforcement; however, it caused little internal damage.

The Impulse Response results showed some areas of high average mobility, so the engineers chose to take core samples at these sites. From the core samples, the concrete appeared to be sound on the surface, but was poorly consolidated underneath, verifying the Impulse Response results. Figure 25 shows a worker taking a core sample from the bridge. Some concrete deterioration is also visible in this image. Figure 26 shows a core sample with poor concrete consolidation inside.



Figure 22. Coring at Putnam County Bridge. Source: Davis et. al. 2001.

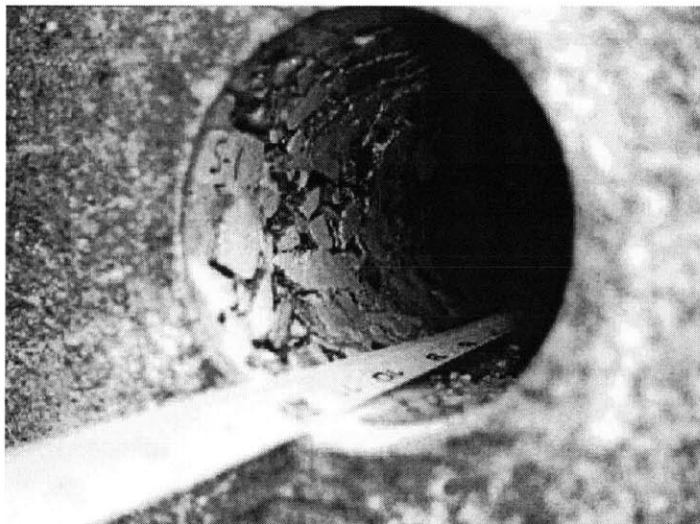


Figure 23. Core hole Source: Davis et. al. 2001.

5.2.3 Former Hong Kong and Shanghai Bank

Recently, engineers in China successfully used GPR to obtain information about a precious historic mural in the the former Hong Kong and Shanghai Banking Corporation building (Figure 27). Most of the information for this topic was provided in the paper *A Case Study—GPR Testing of Shanghai Historical Bank Building*, by Xiongyao Xie and Yonghui Zhao. The paper was

published in the proceeding of the *Ninth International Conference on Ground Penetrating Radar*. The Hong Kong and Shanghai Banking Corporation was built in 1923 in the Bund in Shanghai. The building was also formerly known as the Shanghai Huifeng Bank Mansion and is currently a hotel.



Figure 24. Former Honk Kong and Shanghai Bank. Source: Gluckman 2003.

During renovations of this building, workers recently uncovered murals in the octagonal ceiling of the first floor. The murals have great historical significance. Workers also found cracks in the rooftop, floor plate, and roof trees¹, which could potentially damage the murals. The engineers wanted to fix the cracks without causing further damage to the murals. Because of the age of the building, they no longer had any plans or records to aid them in the restoration process. They decided that they could only use NDE in order to ensure that the murals would not be damaged.

¹The paper, *A Case Study—GPR Testing of Shanghai Historical Bank Building*, by Xiongyao Xie and Yonghui Zhao, appears to be either translated or written in a second language. Some of the translations, such as “roof trees” appear to be incorrect. The author has tried to preserve the original language of the text in this document. She assumes that the term “roof trees” may mean columns.

The engineers first considered using ultrasonic testing on the ceiling. However, they determined that there were disadvantages to ultrasonic testing. In this situation, the concrete is located behind a wooden plate that is located behind the fresco, making ultrasonic detection difficult. Also, ultrasonics would not be able to accurately show the position of the reinforcing steel in the concrete.

After ruling out ultrasonic testing and considering several other methods, investigators finally chose to use GPR. The investigators chose this method because it is nondestructive, has a high resolution, can be used continuously, and is fast and convenient.

The engineers working on this project had to carefully understand GPR before they could apply it. They determined that for reinforced concrete structures, the concrete must be considered the uniform medium while the steel is the “abnormality.” So, when the electromagnetic waves of the GPR testing devices are released, the engineers should obtain a strong wave reflection at the concrete-steel interface. They should also be able to determine the location of the rebar without any interference from the concrete.

In the case of a steel plate (such as the flange of a W-section), the steel plate would again be the abnormality. Again, there would be a strong electromagnetic reflection; however, the horizontal plane causes the wave to be diffracted.

If a void is present, the electromagnetic wave will change polarity after it is reflected. This will cause multiple reflections.

The goal of the testing was to determine the (1) location and size of rebar, (2) location and size of steel plates, (3) concrete thickness, and (4) concrete defects. To perform the GPR testing, the engineers worked on an orthogonal grid with lines at 1-cm intervals on the wall, floor plate, and roof trees. They also created a grid of 40 orthogonal lines at 5-cm-long intervals on the

floor above the mural, which they used to help determine the contact between the mural and the floor plate and beam.

Prior to testing on the mural, the engineers first analyzed an area where they already knew the location of the steel reinforcement and the concrete thickness. The GPR test produced accurate results, verifying the validity of the test.

From the examination, the investigators were able to determine that the cross-section of the orthogonal ceiling has a steel reinforcement grid. The steel is arranged at 15-cm intervals in the x-direction and 30-cm intervals in the y-direction. They determined the wall thickness (20 cm), and that there is an 8 cm protective layer of concrete.

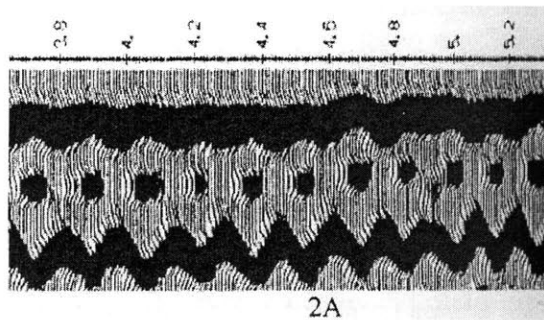


Figure 25. GPR imaging of concrete rebar. (Source: Xie et. al. 2002)

The investigators also tested to determine the size and location of the beams in the ceiling. By performing the test in each of the three principal axes (x, y, and z directions), they were able to determine the location and size of the concrete encased beams. They determined that they had a flange width of 32 cm, a web of 63 cm, and were spaced at an interval of 30 cm.

One of the most important issues that the engineers were interested in was the contact relationship between the mural, the floor plate, and the beams. From the GPR testing, the engineers were able to determine the presence and location of metallic anchor bolts, which were

transfer mechanisms for the interaction force. From this data, they were able to generate a cross section of the results. Figures 29 and 30 show the locations of the anchor bolts.

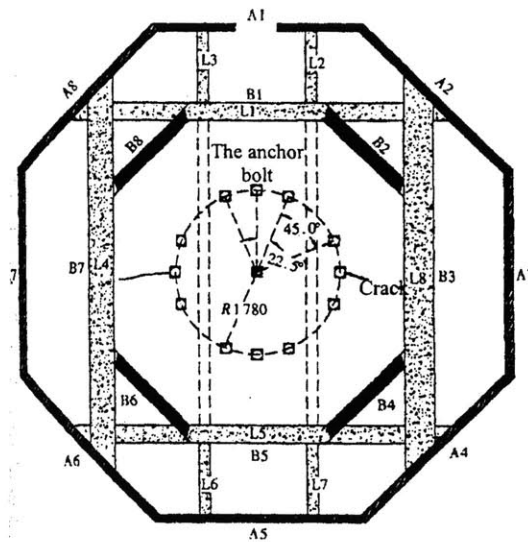


Figure 26. Plan view of octagonal ceiling showing anchor bolt locations. (Source: Xie et. al. 2002)

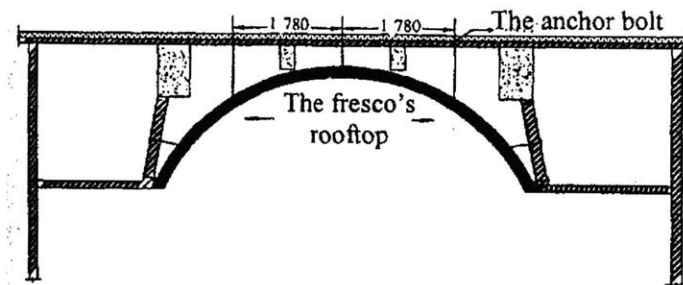


Figure 27. Cross-section of octagonal rooftop showing anchor bolt connections. (Source: Xie et. al. 2002)

6.0 CONCLUSION

Nondestructive testing and evaluation can reveal a great deal of information about a structure without damaging it. NDE is particularly applicable to historic structures, because it is especially important to limit damage on these irreplaceable treasures.

In general, it is often less expensive to replace an historic structure than to rehabilitate it. Subsequently, any decision to restore an historic structure is usually dependent on the structures historical significance to the owner.

Typically, NDE tests are most suitable for homogeneous materials such as steel. However, most historic structures are composed of heterogeneous materials such as masonry and concrete. NDE methods for heterogeneous materials are still being refined and developed, however several have been successfully applied to historic structures. Techniques such as Impulse-Echo, Ground Penetrating Radar, Impulse Response, and Infrared Thermography have been some of the most successful in determining material quality and locating anomalies in heterogeneous materials.

However, all NDE techniques must be used wisely. Only a qualified NDE technician can accurately interpret testing results. It is also important to note that there is rarely a case where a single nondestructive test can provide all of the information needed on a structure. NDE technicians must often employ several tests to gain an accurate understanding of the structure.

Despite the success of these testing methods on historic structures, there is still a need for further study and development of nondestructive techniques.

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