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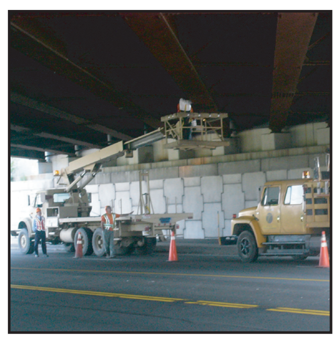


Technical Report MCEER-06-0008

August 21, 2006

This research was conducted at the University at Buffalo, State University of New York and was supported by the Federal Highway Administration under contract number DTFH61-98-C-00094.

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Jianwei Song,[1] Zach Liang,[2] and George C. Lee[3]

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Preface

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a national center of excellence in advanced technology applications that is dedicated to the reduction of earthquake losses nationwide. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission is to reduce earthquake losses through research and the application of advanced technologies that improve engineering, pre-earthquake planning and post-earthquake recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

MCEER's research is conducted under the sponsorship of two major federal agencies, the National Science Foundation (NSF) and the Federal Highway Administration (FHWA), and the State of New York. Significant support is also derived from the Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

The Center's Highway Project develops improved seismic design, evaluation, and retrofit methodologies and strategies for new and existing bridges and other highway structures, and for assessing the seismic performance of highway systems. The FHWA has sponsored three major contracts with MCEER under the Highway Project, two of which were initiated in 1992 and the third in 1998.

Of the two 1992 studies, one performed a series of tasks intended to improve seismic design practices for new highway bridges, tunnels, and retaining structures (MCEER Project 112). The other study focused on methodologies and approaches for assessing and improving the seismic performance of existing "typical" highway bridges and other highway system components including tunnels, retaining structures, slopes, culverts, and pavements (MCEER Project 106). These studies were conducted to:

- assess the seismic vulnerability of highway systems, structures, and components;
- develop concepts for retrofitting vulnerable highway structures and components;
- develop improved design and analysis methodologies for bridges, tunnels, and retaining structures, which include consideration of soil-structure interaction mechanisms and their influence on structural response; and
- develop, update, and recommend improved seismic design and performance criteria for new highway systems and structures.

The 1998 study, "Seismic Vulnerability of the Highway System" (FHWA Contract DTFH61-98-C-00094; known as MCEER Project 094), was initiated with the objective of performing studies to improve the seismic performance of bridge types not covered under Projects 106 or 112, and to provide extensions to system performance assessments for highway systems. Specific subjects covered under Project 094 include:

- development of formal loss estimation technologies and methodologies for highway systems;
- analysis, design, detailing, and retrofitting technologies for special bridges, including those with flexible superstructures (e.g., trusses), those supported by steel tower substructures, and cable-supported bridges (e.g., suspension and cable-stayed bridges);
- seismic response modification device technologies (e.g., hysteretic dampers, isolation bearings); and
- soil behavior, foundation behavior, and ground motion studies for large bridges.

In addition, Project 094 includes a series of special studies, addressing topics that range from non-destructive assessment of retrofitted bridge components to supporting studies intended to assist in educating the bridge engineering profession on the implementation of new seismic design and retrofitting strategies.

The major objective of this report is to evaluate various nondestructive testing/evaluation (NDE) technologies for use on bridge columns that have been retrofitted with FRP-type jackets. Suitable and/or potentially suitable techniques for practical applications are identified, and promising techniques that could benefit from additional research prior to use in engineering applications are assessed. For each technology, the inherent physical principles and application characteristics are analyzed and their advantages and disadvantages are compared to determine whether each method could be used to detect damage and defects in the jacketed bridge columns. The most promising NDE methods (such as the impact echo method and electromagnetic method) are identified and corresponding application procedures are then presented. This report focuses solely on the application of NDE technologies to bridge columns, and therefore, recommendations and conclusions herein may differ from those discovered for other applications. Furthermore, this is a rapidly advancing field, so some applications and conclusions may change in the coming years.

ABSTRACT

Reinforced concrete columns of highway bridges may need to be seismically strengthened due to the aging process, damage caused by small to mid-level earthquakes, or new seismic specification requirements. Implementing steel or composite jackets to retrofit such columns is one of the most commonly employed methods. In addition, during the last decade, more and more researchers and engineers have recognized that carbon or glass fiber-reinforced polymers (C-FRP or G-FRP) composites can offer many significant advantages in ductility and cost for column retrofit over traditional materials such as steel and concrete. Thus, an increasing number of old highway bridge columns have been retrofitted with FRP composite jackets during the last decade.

However, if the bridge is subjected to an earthquake again, the structural condition inside the retrofitted portion of the columns covered by jackets may change, which is very difficult to detect. Therefore, determining how to apply and/or develop appropriate non-destructive testing/evaluation (NDT/NDE) technologies to assess this type of damage is an important issue. This report reviews existing research and considers pros and cons for potential application of NDT/NDE to retrofitted bridge columns with jackets, where FRP-type jackets are emphasized for consideration.

The application history of FRP and NDE in highway bridges is briefly reviewed. Then, the general state-of-practice of NDE technologies, which have been developed and applied to highway bridges are evaluated. The inherent physical principles and application characteristics for each technology are analyzed and their advantages and disadvantages are compared. Furthermore, the applicability of each method for use in defect and damage detection for jacketed bridge columns is explored. The most likely candidate NDE methods are identified (impact echo method and Electromagnetic method) and corresponding application procedures are suggested.

In the past decade, NDT/NDE as well as system health monitoring technologies have attracted attention in various fields. In many cases, these technologies have achieved great success and a newly developed industry for corresponding hardware and software has developed both in the U.S. and throughout the world. This report focuses only on the current status of techniques to evaluate retrofitted bridge columns. Therefore, many interesting techniques as well as theories in damage modeling, signal measurement and processing, and system identifications are excluded. The authors wish to note that there are many excellent reports on NDT/NDE technologies and applications. This report focuses solely on their application to bridges, and therefore, recommendations and conclusions herein may differ from those discovered for other applications. Furthermore, this is a rapidly advancing field, so some applications and conclusions may change in the coming years.

ACKNOWLEDGEMENTS

The authors thank Dr. Maria Feng of the University of California at Irvine for reviewing this work. Her input and suggestions have helped make this a successful research endeavor.

This research was conducted by the State University of New York at Buffalo and was supported by the Federal Highway Administration under contract number DTFH61-98-C-00094 to the Multidisciplinary Center for Earthquake Engineering Research. However, any opinions, findings, conclusions and recommendations presented in this report are those of the authors and do not necessarily reflect the views of the sponsors.

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CHAPTER 1
INTRODUCTION

1.1 Goals, Scope and Report Organization

Following a strong earthquake, a bridge owner is most concerned about whether a particular bridge has been damaged and if so, to what extent, and whether the bridge safe is enough to allow continued traffic. If damage is obvious, these questions may be relatively easily answered by an experienced engineer through visual inspection, and/or aided by non-destructive testing/evaluation (NDT/NDE) methods when assessing a bridge that has not been retrofitted. However, if the bridge columns have been retrofitted with either steel or FRP jackets, the damage may not be visible or easy to detect. In this case, one or more combined special and appropriate NDT/NDE technologies are needed to determine if damage has occurred.

Although there are many different NDT/NDE methods, those that are appropriate for rapid post-earthquake evaluation of bridges have not been specifically identified or, for the most part, validated against jacketed bridge columns. The objective of this research is to review and assess current NDE methodologies to determine if they can be used to evaluate damage in reinforced concrete columns that have been retrofitted using steel or composite jackets.

Figure 1-1 describes the relationship between bridge column retrofit with FRP and NDE/NDT applications. There are three NDE/NDT application stages:

1. After the bridge has been subjected to an earthquake or has suffered deterioration.

2. After bridge columns are retrofitted (for FRP installation quality control).

3. After the retrofitted bridge columns have been subjected to an earthquake again.

In this report, the third stage of NDE/NDT applications for FRP-jacketed highway bridge columns are emphasized for two reasons:

1. Available post-earthquake technologies are more challenging and encompass technologies used in the first and second stages; and

2. FRP materials are more commonly used than steel to retrofit bridge columns during the last decade in the U.S. and elsewhere.

This report provides an overview of the application of NDE for damage detection in FRP/steel jacketed retrofit for highway bridge columns. The general state-of-practice of NDE technologies, which have been developed and applied to highway bridges, are evaluated. The inherent physical principles and application characteristics are analyzed for each technology and their advantages and disadvantages are compared in order to determine whether each method could be used to detect damage and defects in the jacketed bridge columns. The most promising NDE methods (such as the impact echo method and electromagnetic method) are identified and corresponding application procedures are then presented. The conclusion presents suggestions for future research.

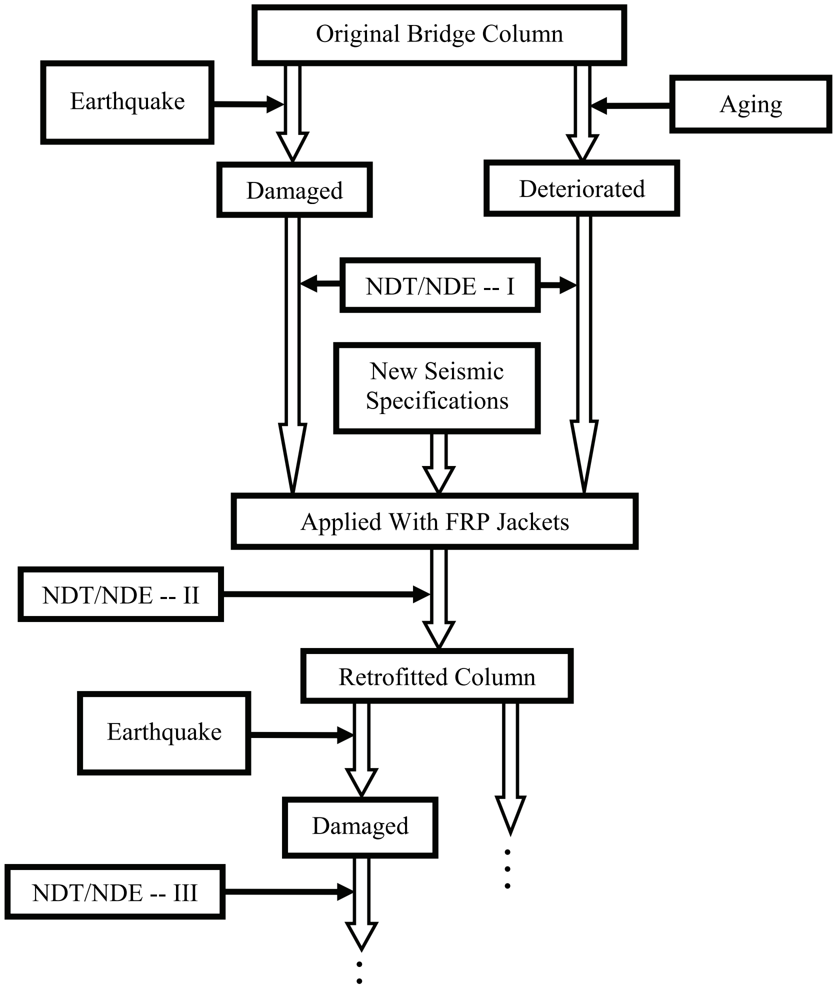


Figure 1-1. NDT/NDE Application to Highway Bridge Columns Before/After Retrofit

1.2 Technology Review

The major objective of this report is to evaluate various NDE technologies for use on retrofitted bridge columns in order to find suitable and/or potentially suitable techniques for practical applications as well as to assess promising techniques that could benefit from additional research prior to use in engineering applications.

Generally speaking, NDT/NDE involves many state-of-the-art technologies in several fields. These include structural engineering, especially bridge engineering; earthquake engineering and the sub-specialty of column retrofitting; sensory and measurement systems, such as microwave, mechanical wave, thermo transducer, and vibration testing, etc.; signal processing and data management; electronic hardware; and system identification and corresponding software. It is understandable that since so many fields are involved, available theoretical knowledge is not thorough or comprehensive, and is far from sufficient to compare and evaluate these methods. In order to present a thorough analysis, these techniques should be tested in a repeated fashion to obtain sufficient data to determine their effectiveness. However, covering such a vast field is very difficult and a major research program would be further required.

Therefore, this report is primarily based on literature surveys and comparisons. It is primarily a survey report, which can be used by other researchers to build experimental data on the most promising methods. These promising methods are recommended by consensus among the most accepted opinions offered in the literature. In addition, in some cases, the authors contacted the original researchers to gain a better, more thorough understanding of some of the methods presented herein.

In this perspective, the conclusions offered should be regarded as preliminary. The authors are open to further discussion on the topics presented herein.

CHAPTER 2
OVERVIEW OF BRIDGE COLUMN RETROFIT AND REHABILITATION

Columns are the most essential and important structural element in a bridge. Structural columns are subjected to both vertical loading effects from the gravity force, and to combined variable axial forces. In a number of cases, columns are retrofitted primarily to stop crack widening and further cracking, which can occur for a number of reasons, such as aging, deterioration, and/or small-to-mid-level earthquakes. Bridge columns are also retrofit to accommodate new seismic specification requirements. These columns may have been originally designed in accordance with the practice that did not account for the importance of plastic deformation and ductility capacity, resulting in a deficiency in flexural ductility, shear strength, and flexural strength under strong seismic excitation.

Even though life safety is ensured, damage from a major earthquake may terminate the bridge function. This was evident following the 1999 Chi-Chi, Taiwan earthquake. The most common deficiency in damaged bridge columns may be characterized as insufficient shear strength or ductility, inadequate anchorage or bonding, and insufficient flexural strength or ductility. To mitigate column damage in future earthquakes, a number of column retrofit techniques have been developed and clarified based on loading tests, such as steel jacketing, concrete jacketing, and composite jacketing. These jackets are primarily used to provide confinement for columns. Currently, fiber reinforced plastics (FRP) are commonly used for retrofitting structures (Seible et al., 1997; Saadamanesh et al., 1996; Tang, 1997 and 2003).

2.1 Steel Jackets

In the steel jacketing method for circular columns, two half shells of steel plate rolled to a radius of half to one inch larger than the column radius are positioned over the area to be retrofitted and are site-welded up the vertical seams to provide a continuous tube with a small annular gap around the column. The gap is grouted with a pure cement grout. Generally, a space of about 50 mm is provided between the jacket and footing or cap beam to avoid excessive flexural strength enhancement of the plastic hinge. The jacket is effective in passive confinement. The level of lateral confinement induced in the concrete by flexible restraint as the concrete attempts to expand laterally in the compression zone depends on the hoop strength and stiffness of the steel jacket. A similar action occurs in resisting the lateral column dilation associated with the development of diagonal shear cracks. In both the confinement of flexural hinges or potential shear failures, the steel jacket is considered to be equivalent to continuous hoop reinforcement.

Rectangular steel jackets on rectangular columns are not generally recommended, although they are expected to be fully effective for shear strength enhancement. For rectangular columns, use of an elliptical is recommended.

Steel jacketing has been widely used in California for lap splice retrofit as shown in figure 2-1. It was the major retrofit technique for bridge columns, with several hundred bridges thus retrofitted by 1994 (Kawashima, 2005; Chai et al., 1990). During the 1994 Northridge earthquake, some 50 bridges with steel jacketed columns were subjected to peak ground acceleration of 0.3g or higher. None of these bridges suffered damage to columns or required subsequent remedial work (Kawashima, 2005).

Steel jacketing has also been used in Japan for retrofit to prevent premature shear failure resulting from termination of longitudinal reinforcement with inadequate development length. After this problem was first recognized due to damage caused by the 1982 Urakawa-Oki earthquake, extensive experimental studies were conducted. Columns which were retrofitted in 1989, as shown in figure 2-2, were subjected to 0.8g or higher peak ground acceleration during the 1995 Kobe earthquake. None of the retrofitted columns suffered damage but the columns which were not retrofitted suffered extensive damage. After the 1995 Kobe earthquake, over 27,000 columns of road bridges were retrofitted in Japan (Kawashima, 2005).

Kawashima 2005, Chai et al., 1990

Figure 2-1. Steel Jacket Retrofit (California Department of Transportation)

Kawashima 2005

Figure 2-2. Steel Jacket Retrofit at Hanshin Expressway, Japan in 1989, which was Effective during the 1995 Kobe Earthquake

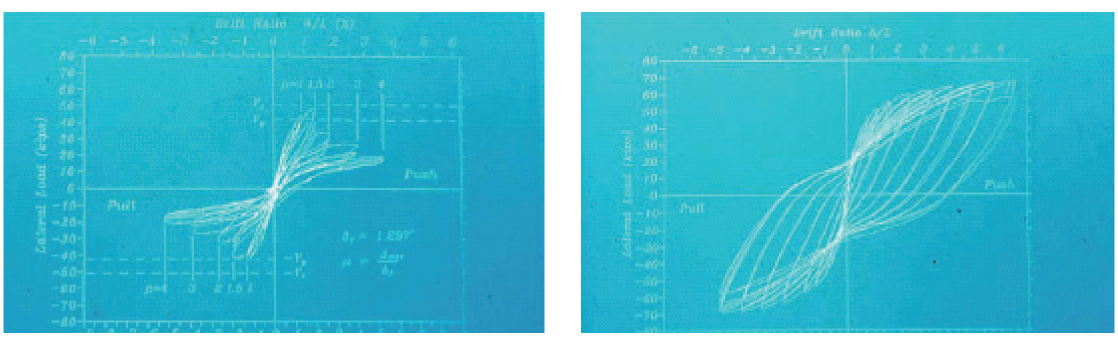
2.2 FRP Jackets

FRP products were first used to reinforce concrete structures in the 1950's. During the next two decades, the quality of the FRP materials improved considerably, manufacturing methods became more automated, and material costs decreased. The use of these materials for external reinforcement of concrete bridge structures started in the 1980's, primarily in Japan (sheet wrapping) and Europe (laminate bonding), first as a substitute to steel plate bonding and then as a substitute for steel confinement shells for bridge columns. The principles behind externally bonding FRP plates or wraps to concrete structures are very similar to the principles used in application of bonded steel plates. In general, the member's flexural, shear, or axial strength is increased or better mobilized by the external application of high tensile strength material.

Today, more and more bridge columns have been seismically upgraded with FRP composites. Ongoing development of cost-effective production techniques for FRP composites has progressed to the level that they are ready for the construction industry. Reduced material cost, coupled with labor savings inherent with its low weight and comparably simpler installation, relatively unlimited material length availability, and immunity to corrosion, make FRP materials an attractive solution for post strengthening, repair, seismic retrofit, and infrastructure security. Figures 2-3 and 2-4 show bridge columns being tested in the lab and lateral load/deflection curves before and after retrofitting with glass FRP respectively (Cruickshank, 2002), while figure 2-5 illustrates a FRP jacket installation for a bridge column in the field (Busel and White, 2003).

Cruickshank, 2002

Figure 2-3. Bridge Columns in a Lab before and after Retrofitting with Glass FRP



Cruickshank, 2002

Figure 2-4. Lateral Load – Deflection Curves of Unretrofitted and Retrofitted Columns

Busel and White, 2003

Figure 2-5. FRP Installation for Bridge Column at Field Sites

For FRP, the following features and benefits can be achieved for repair, strengthening and seismic retrofit of columns:

- **Repair:** FRP composite systems can be used to repair damaged concrete structures. The FRP is used in combination with resin crack injection, cementitous repair mortars, epoxy grouts, etc., to repair the section and restore it to pre-damaged load ratings. Repair of concrete structures caused by corroding steel rebar can be accomplished, provided the corroded elements are repaired or replaced and the sources of corrosion are addressed. The repair of any element in a structure must be approached in a project-specific manner. The type of composite, the number of layers, the orientation of fibers, and the preliminary work and surface preparation all depend on the design goals and type of structural element as determined by the project.

- **Strengthening:** FRP composite systems can be used to strengthen undamaged concrete structures that require greater load capacity due to functional changes, additional loads, code changes or other reasons. The FRP is placed on tensile surfaces in a manner similar to steel plate bonding for strengthening or embedded into saw cut grooves near the concrete surface. FRP composite systems can add shear and flexural strength to beams and slabs for both positive and negative moment conditions. Strengthening of existing concrete structural members with FRP composites is accomplished by utilizing the tensile strength and stiffness of the composite and the strain compatibility of the composite to the existing member. The design must include proper selection of the adhesive used to bond the FRP reinforcement to the surface of the concrete to be strengthened. As in repair, the type of composite, the number of layers, the orientation of fibers, and the preliminary work and surface preparation all depend on the design goals and type of structural element as determined by the project.

- **Seismic Retrofit:** FRP composite systems have been used extensively in seismic zones for confinement of concrete columns and walls. A number of FRP systems have been qualified for use by State DOTs for wrapping circular and rectangular bridge columns. Improvements in ductility factors of up to 10 times have been realized through the use of FRP column wrapping. Specific FRP systems, offered by some of the manufacturers, address seismic requirements according to the load capacities anticipated and geometric considerations of the building structure. In addition, FRP systems can be used for stabilizing hollow clay tile, brick and other unreinforced and lightly reinforced masonry walls in life-safety applications where vital egress and exit paths in buildings are required.

The efficiency and improvement of the seismic performance of highway bridge columns with FRP jackets have been demonstrated by structures that have survived following recent earthquakes. For example, Columns I5/Hwy 2 interchange, Los Angeles (shown in figure 2-6), where the columns were retrofitted with FRP in 1991, following seismic analysis which showed they were severely deficient. After the 1994 Northridge earthquake, post earthquake inspection revealed that these columns performed as designed during the seismic event with no damage to the roadway at that location. As a contrast, just north of this interchange, the I5/SH-14 interchange collapsed, demonstrating how vulnerable highway columns without proper retrofits are to seismic events (Cruickshank, 2002).

Cruickshank, 2002

Figure 2-6. Columns I5/Hwy 2 Interchange, Los Angeles

2.3 Comparison Steel and Jackets

Traditional retrofit materials are steel and concrete. A steel jacket retrofitted column exhibited a slightly higher initial stiffness and a slight increase in lateral load carrying capacity with increasing displacement levels due to the isotropic nature of the steel, resulting in a more concentrated plastic hinge and more strain hardening at the column ends. Both stiffness and capacity increases are not sought for in bridge – or even building - column retrofits since typically higher seismic force levels are transmitted to adjacent structural elements. Thus, the glass fiber jacket with mainly horizontal or hoop directional strength and stiffness can accommodate the requirement for stiffness or strength increase even better than a steel jacket.

Tests on circular columns retrofitted with FRP jackets to improve ductility indicate that the confinement effectiveness is more efficient than with steel jackets[1]. It is thought that this is the result of the elastic nature of the jacket material. With a steel jacket, yield under hoop tension may occur early in the seismic response. On unloading, residual plastic strains remain in the jacket, reducing its effectiveness for the next cycle of response and requiring increased hoop strains for each successive cycle. With materials such as fiberglass and carbon fiber, which have essentially linear stress-strain characteristics up to failure, there is no cumulative damage and successive cycles to the same displacement result in constant rather than increasing hoop strain. Thus, the experimentally derived expression for FRP jackets indicates greater efficiency than for steel jackets. Figure 2-7 summarizes the advantage and disadvantage for steel and FRP jackets.

Steel Material Jacket:

- Low Material Cost
- High Installed Cost
- Higher overall Cost
- Corrosive
- Heavy
- Fabrication Required
- High Maintenance
- Less Efficiency
- Large Effect on the Appearance of the Structure
- Insensitive to Mechanical Attacks and Higher Temperature (Vandalism)

FRP Material Jacket:

- High Material Cost
- Low Installed Cost
- Lower overall Cost
- Non-Corrosive
- Light Weight
- No Fabrication Required
- Low Maintenance
- Higher Efficiency
- Small Effect on the Appearance of the Structure
- Sensitive to Mechanical Attacks and Higher Temperature (Vandalism)

Figure 2-7. Comparison for Steel Material Jacket and FRP Material Jacket

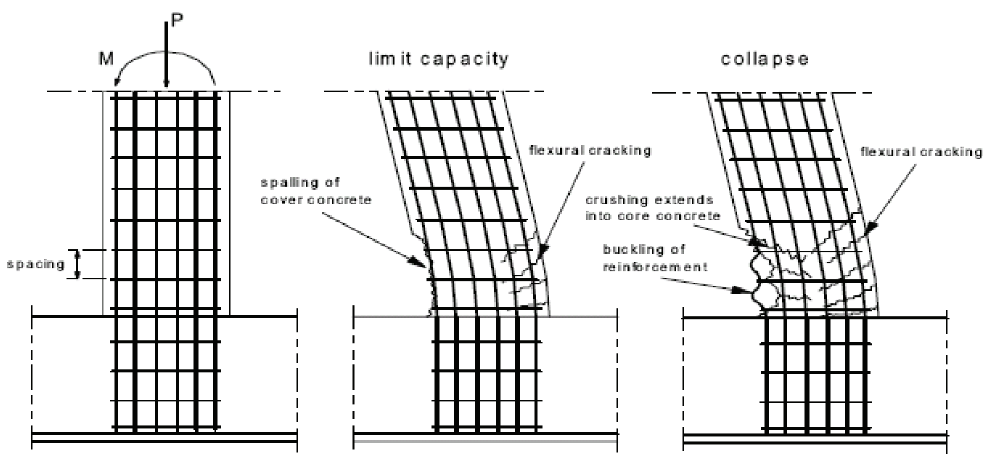
[1] Kundu et al.,1999; Haroun et al., 2003; Chai et al., 1990; Hollaway and Leeming, 1999; Li and Sung, 2004; Priestley et al., 1996; Hosseini and Fadaee, 2004; Zhanga et al., 2003; Ye et al., 2003; Saiidi et al., 2004; Pessiki et al., 2001; Mirmiran et al., 2004; Tang 1997 and 2003; Busel and White, 2003; Pesˇic´ and Pilakoutas, 2003; Parvin and Wang, 2002; Monti et al., 2001; Pantelides et al., 2004; Van Den Eindea et al., 2003

2.4 Bridge Column Failure Mode

2.4.1 Failure Mode of Bridge Column without FRP Retrofits

The majority of lab experiments and earthquake investigations indicate the most critical mode of failure is the brittle column shear failure where inclined cracking leads to the concrete cover spalling and to the rupture or opening of the stirrups. Another mode consists of a confinement failure of the plastic hinge region, where subsequent to flexural cracking, cover concrete crushing and spalling, buckling of the longitudinal reinforcement or compression failure of concrete initiates plastic hinge deterioration, usually limited to shorter regions in the column. It can also happen that the column fails to the debonding of the lap splices of the longitudinal reinforcement. The associated flexural capacity degradation can occur rapidly at low flexural ductilities in cases where short lap splices are present and little confinement is provided.

Figure 2-8 demonstrates the lateral collapse mechanism of an under-designed column without FRP Jacketing (Monti, 2003), while figure 2-9 shows real-world shear failure and collapse of bridge columns following the Chi-Chi earthquake in Taiwan (Photograph by I.G. Buckle/MCEER, 1999).



Monti, 2003

Figure 2-8. Lateral Collapse Mechanism of an Under-designed Column without FRP Jacketing

I.G. Buckle/MCEER, 1999

Figure 2-9. Shear Failure of Bridge Columns in Chi-Chi Earthquake, Taiwan

2.4.2 Failure Mode of Bridge Column with FRP-Jacketed Retrofits

Since a jacket is made of several layers of FRP composites often manually or automatically applied to the column, layer by layer, glued with adhesive epoxy, the composite material and bonding quality becomes a very important issue. A number of studies (Saadamanesh et al., 1996; Seible et al., 1997; Haroun et al., 2003) showed that debonding and delamination between the layers of the composite and between the jacket and the column can considerably weaken the column either during installation or following an earthquake.

By analyzing the mechanism of a FRP-jacketed bridge column loading and damage, shown in figure 2-10, ten possible failure modes of a reinforced concrete column jacketed with FRP can be summarized as follows:

1. Debonding of glue and concrete
2. Debonding of the glue and FRP layer
3. Delamination of the FRP
4. Failure of reinforced bars (rarely happened)
5. Crushing of the concrete
6. Peeling off of the concrete
7. Cracking of the concrete
8. Cracking in the FRP layer
9. Cracking in the glue layer
10. Failure of the FRP layer

Figures 2-11 and 2-12 show the experimental examples of delamination and cracking in the FRP layer/concrete, respectively.

These failure modes may occur as a single event or in combination with other factors, which may significantly weaken the structural performance of the column. By using candidate NDT/NDE methods, single and multi-defects may be detected.

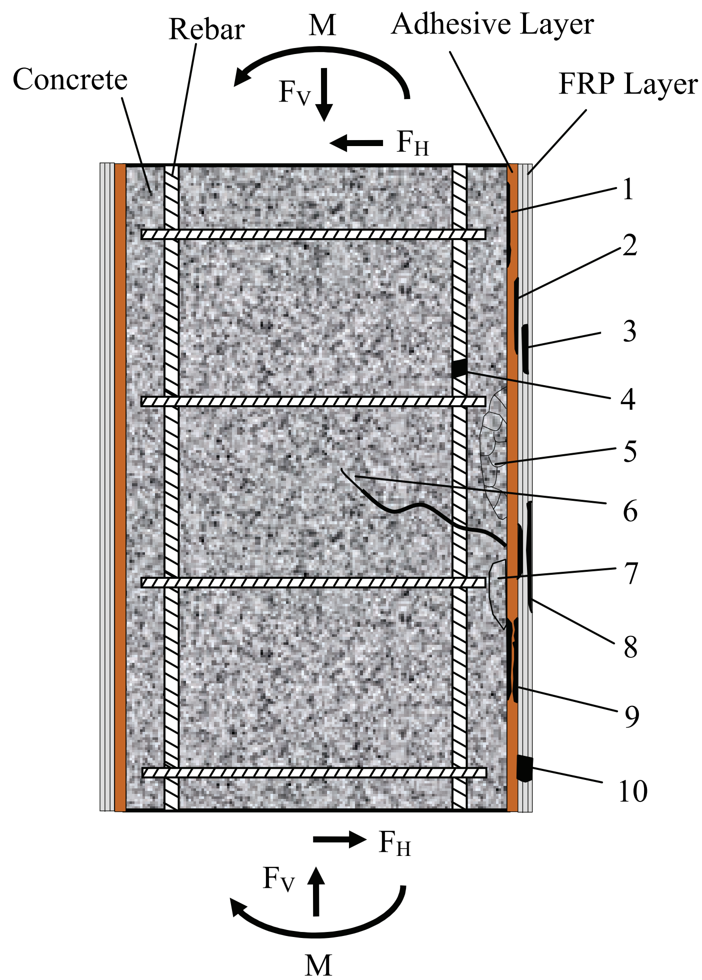
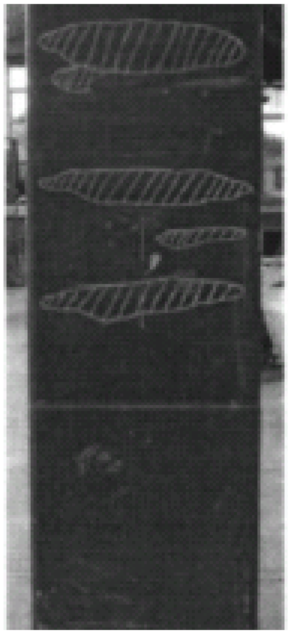


Figure 2-10. Failure Mode of RC Bridge Column Jacketed by FRP



Hosseini and Fadaee, 2004

Figure 2-11. Delamination of FRP

Hosseini and Fadaee, 2004

Figure 2-12. Cracking in the FRP Layer and the Concrete

CHAPTER 3
BRIEF INTRODUCTION TO NDT/NDE METHODS CURRENTLY USED FOR HIGHWAY BRIDGES

3.1 Necessity of NDT/ NDE Technologies for Highway Bridges

Major Points:

- High percentage of highway bridges in the United States are experiencing or starting to experience deterioration as they approach the end of their service life and have larger than expected service.
- After a bridge is subjected to an earthquake, its structure may be damaged.
- Repair, retrofit, rehabilitation and replacement become necessary to ensure the public safety.
- The type of action taken depends on an accurate assessment of the bridge condition and limited maintenance budget.
- A major challenge is to not only inspect the external appearance of bridges, but also their internal conditions.
- Nondestructive testing/evaluation (NDT/NDE) is effective for inspecting internal bridge conditions.
- Most NDT/NDE technologies are based on mechanical and electromagnetic wave propagation approaches.

The Federal Highway Administration (FHWA) currently maintains an inventory of 584,318 bridges in the United States. Of these, 281,874 were built between 1951 to 1980, with a design service life of approximately 50 years (FHWA, 1997). As a result, many are experiencing or starting to experience deterioration as they approach the end of their service life. Statistical data have shown that nearly one-third of these bridges are either structurally or functionally deficient. As a consequence, the bridges built in this period have grown old and may soon require replacement or major repairs.

On December 15, 1967, the collapse of the Silver Bridge over the Ohio River between West Virginia and Ohio, led to national concern about the safety of each bridge in the United States. Consequently, Congress was urged to create a national bridge inspection program. It became important to develop rational procedures to determine the actions and their associated costs, which need to be taken to provide safety and a satisfactory level of bridge service. Efficient and reliable diagnostic methods to evaluate the remaining capacity and service life of a bridge are critical tools used by infrastructure management agencies.

Bridge failure occurs as a result of factors such as corrosion, fatigue, inappropriate design, overload, wind, scour, earthquake, floods, and fire. In most cases, failures can be prevented by periodic maintenance inspections and retrofits. AASHTO has developed a "Manual for Condition Evaluation of Bridges" (1994), which provides for uniformity in the procedures and policies for determining the physical condition, maintenance needs, and load capacity of highway bridges. Following recent bridge collapses or near collapses, researchers have focused on the need to develop extensive nondestructive evaluation (NDE) techniques for real-time structural damage assessment to help guarantee the safety of the nation's transportation system. Real-time NDE techniques can immediately provide information such as size, shape, location, and orientation of discontinuities as part of the structural damage assessment.

There are many NDT/NDE techniques. Each technique is based on different theoretical principles and relies on waves of various types to assess the condition of a specimen under test.[2] There are two fundamental classes of waves that are used in NDE. The first is mechanical waves, sometimes called acoustic waves. This wave propagates by small displacements of matter, and requires a medium in order to propagate. The second class of waves is electromagnetic waves. These waves propagate by changes in the electrical and magnetic state and do not require a medium. When electromagnetic waves propagate through matter, the matter is generally not displaced from its initial position; instead, only its electrical and magnetic states are changed.

Mechanical Waves

Mechanical waves propagate through a medium by a series of displacements to that medium. Mechanical waves can exist over a broad range of frequencies. At the low frequency range, in the range of hertz, are structural displacements such as the periodic vibrations of a bridge. The audible range of a mechanical wave is between 20 hertz and 20 kilohertz. Ultrasonic testing instruments typically range between 30 kilohertz to 10 Megahertz. Because mechanical waves cause displacements in the medium in which they propagate, the propagation velocity is affected by the properties of the medium. Specifically, the stiffness of the medium, or modulus, has a significant effect on the propagation velocity, as does the density of the medium (Washer, 1998, 2000, 2004a and b).

One of the most commonly used phenomena in mechanical testing is the effect on wave propagation of sudden changes in acoustic impedance. The acoustic impedance of a material is a function of the material's elastic modulus and density. When a wave propagates from one material with impedance to another material with different impedance, a portion of the wave will be reflected as a result of the interaction of the wave with the boundary between the two materials. For example, if a wave is propagating through a concrete block and there is a crack in the block, a majority of the wave will be reflected at the boundary of the intact concrete. This effect is commonly used in ultrasonic testing to detect subsurface defects in welds (Washer, 1998, 2000, 2004a and b).

Electromagnetic Waves

Electromagnetic waves also exist over a broad range of frequencies. Low frequency waves include radio and television broadcasts, and higher frequency waves include microwaves generated in a microwave oven. At still higher frequencies, the human eye can detect electromagnetic waves, and these are observed as light of various colors (figure 3-1). Waves at very high frequency include x-rays and gamma rays. Due to the high frequencies of these waves

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[2] Malhotra and Carino, 2004; Bray and Stanley, 1997; Washer, 1998, 2000, 2004a and b; Chang and Liu, 2003; McCann and Forde, 2001; Rens et al., 1997, 2005; Sack and Olson, 1995; Olson and Church, 1986; Martin et al., 1998; USACE 1998; Popovics 2003; Kaiser and Karbhari, 2001, 2002; Ciolko and Tabatabai, 1999; Phares 2004

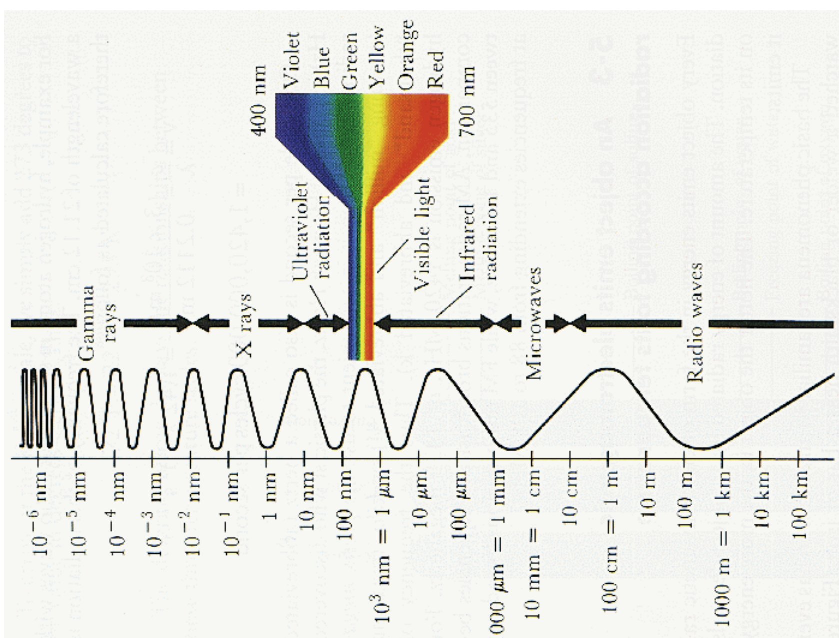
and their small wavelengths, they pass through dense materials; this property is used to generate x-ray images.

A key parameter in the propagation of electromagnetic waves in solid materials is the dielectric constant. The dielectric constant (in part) is a measure of the velocity of the wave propagation within the material, and relates to the impedance of the material. As with mechanical waves, changes in dielectric properties cause waves to be reflected. This property is used in ground penetrating radar systems to detect subsurface defects that cause reflections.

There are five major factors which need to be considered in the application of a NDT based on these various waves, as follows (McCann and Forde, 2001):

1. The required depth of penetration into the structure.
2. The vertical and lateral resolution required for the anticipated targets.
3. The contrast in physical properties between the target and its surroundings.
4. Signal to noise ratio for the physical property measured at the structure under investigation.
5. Historical information concerning the methods used in the construction of the structure.

Careful application of all these factors to the design of a NDT survey should result in a specification which either achieves the desired objectives or, more importantly, recommends an alternative approach if no NDT surveying method is deemed appropriate to solve a given problem. Some examples of the importance of these factors are presented below; the principles of the different methods that can be used are described later in the text.



Washer, 1998, 2000, 2004a and b

Figure 3-1. Electromagnetic Wave Spectrum and Relationship between Wavelengths and Common Terms for Various Portions of the Spectrum

The most common problem that an NDT specialist faces in dealing with the client during the investigation of a structure is the integration of the fundamental information derived from the construction records with the results from the NDT survey. The construction record plus any additional engineering assessment represents the most accurate information that can be obtained on the structure. The actual resolution that can be achieved with all NDT methods will be inferior to the precise measurements obtained from the original plans of the structure. For example, vertical resolution is defined as the smallest vertical dimension, Z_{min}, that can be detected, and this is normally expressed as:

$$Z_{min} = \lambda / 4 \qquad (3\text{-}1)$$

where λ is the dominant wavelength of the NDT data being analyzed.

For an impulse radar survey, the resolution achieved is a function of the frequency of the incident electromagnetic energy and its velocity of propagation. Practical use of impulse radar indicates that the shallowest target that can be identified below the surface of a structure is λ/3, and within a structure, the minimum size of target is a value of λ/2. The differences that the NDT interpreter is faced with are illustrated by the calculations.

Clearly, from the calculations, it is important to select the optimum frequency to achieve the maximum penetration into a structure, coupled with the required resolution of the likely targets.

It is also essential that there is a contrast in the physical properties of the materials within the structure — since there will be no resolution of any significant changes in the engineering properties unless these cause contrasts in physical properties, such as sonic velocity, dielectric properties and so on. Different physical properties can also be a problem; for instance, there is very little difference in sonic velocity between a material saturated with fresh water and one saturated with a saline solution. The same materials would be significantly different as far as electromagnetic properties are concerned, since the material saturated with a saline solution will have a much higher attenuation coefficient than the one saturated with freshwater.

A brief technical description of each of the NDT/NDE methods is presented below, followed by a discussion of evaluation of NDT/NDE techniques that have been applied to jacketed RC highway bridge columns.

3.2 Visual Inspection Method

As previously mentioned, many nondestructive evaluation (NDE) techniques rely on waves of various types to assess the condition of a specimen under test. For visual inspection, light waves reflected from the specimen surface are detected by an inspector's eye, and analyzed by an inspector's brain to determine the identifying specimen's condition (Washer, 2004a; Phares, 2004). The visual inspection method is the oldest and the most commonly used NDE technique, which is considered to be an essential aspect of identifying deficient bridges. A well-trained examiner team follows the National Bridge Inspection Standards (NBIS) inspection requirements/procedure, aided by some simple and necessary tools, to identify fracture cracks, determine the severity of known damage, predict the likely occurrence of failures, and rate the conditions for all primary components of the inspected bridges. The results from the visual inspection can be employed to further guide NDE.

Visual inspection is the simplest NDE technique, and should be the first step in assessing a highway bridge. Using visual inspection, technical personnel can quickly develop a qualitative assessment of the relative structural integrity of individual members. Obvious deficiencies can be easily identified, including external damage, decay, crushed fibers in bearing, creep, or presence of severe checks and splits. The tools used to carry out a visual inspection are shown in Figure 3-2.

Visual inspection is very useful; however, it has definite limitations. Variability stems from differences in visual acuity and training/experience of personnel. Access also poses problems. Components with limited access may be susceptible to increased error in interpretation of visual inspection, and unexposed components cannot be inspected at all. The results are qualitative, rather than quantitative, and knowledge is limited to the exterior surface of the bridge substructure.

Traditionally, the quality of a bridge inspection has been subject entirely to the experience and skill of the inspector—in other words, to human factors. In 2001, the Federal Highway Administration (FHWA) published a comprehensive study entitled “Reliability of Visual Inspection of Highway Bridges” (Code of Federal Regulations, 2004). The following statement is from the introduction to the FHWA report (Hartle et al., 1995; Phares, 2004):

> The visual inspection method is the predominant nondestructive evaluation technique used for bridge inspection and serves as the baseline with which many other NDE techniques may be compared.

Phares, 2004

Figure 3-2. Visual Inspection Tools and Inspecting Operations

> Although it is unlikely that the trained human eye will ever be superseded as an NDE instrument, an increasing array of NDE technology is being effectively adapted for evaluation of bridges and other structures. In the hands of a skilled inspection team, the right mix of NDE technology provides a well-stocked toolbox for accurate assessment and diagnosis.

3.3 Impact Echo Method

The impact echo method was originally developed to measure concrete thickness and integrity from one surface. The method is performed on a point-by-point basis by using a small instrumented impulse hammer to hit the surface of a structure at a given location and recording the reflected energy with an accelerometer mounted adjacent to the impact location. Since reflected signals are more easily identified in the frequency domain, the received energy recorded in the time domain is passed to a signal analyzer for frequency domain analysis — using a Fourier transform algorithm such as fast Fourier transform (FFT). A transfer or frequency response function (FRF) is then calculated for the impulse hammer/accelerometer system and reflections or echoes of the compressional wave energy are indicated by pronounced resonant frequency peaks in the transfer function or frequency spectrum record. These peaks correspond to the thickness or flaw depth resonant frequencies, and if the compressional wave velocity in concrete or any other construction material is known, the depth to the corresponding flaw can be calculated. The depth of the reflector will correspond to the slab or wall thickness if the concrete used in construction is sound.

Impact-echo testing of bridges has largely been focused upon identifying voids in ducts in post-tensioned concrete bridges. In practice, it is often not that straightforward.

Tapping an object with a hammer is one of the oldest forms of nondestructive testing based on stress wave propagation, which is widely used for a quick evaluation of accessible surfaces to detect the presence of delamination, debonding, and voids. It is done by lightly tapping the surface of the object with a small hammer. Depending on whether the result is a high-pitched “ringing” sound or a low frequency “rattling” sound, the integrity of the member can be assessed. The “ringing” sound and “rattling” sound can be relatively compared to that of a known good area. The method is subjective, as it depends on the experience of the operator, and it is limited to detecting near surface defects. Despite these inherent limitations, sounding is a simple and useful method for detecting near-surface delamination, and it has been standardized by the American Society of Testing Material [ASTM, D 4580].

With the development of computer, sensor and signal processing technology, electronic “hearing” transducers and input/response digital signal processing based on a PC have been applied. The first successful applications of impact methods occurred in geotechnical engineering to evaluate the integrity of concrete piles and caissons (Steinbach and Vey, 1975). The technique became known as the sonic-echo or seismic-echo method. The long length of these foundation structures allowed sufficient time separation between the generation of the impact and the echo arrival, and determination of round-trip travel times was relatively simple (Lin et al., 1991; Carino, 2001a). The impact response of thin concrete members, such as slabs and walls, is more complicated than that of long slender members. Work by Sansalone and

Carino[3] however, led to the development of the impact-echo method, which has proven to be a powerful technique for flaw detection in relatively thin concrete structures.

Figure 3-3 is a schematic of an impact-echo test on a plate with a large air void below the surface. As was discussed, impact on the surface produces P- and S-waves that travel into the plate and a surface wave (R-wave) that travels away from the impact point. The P- and S-waves are reflected by internal defects (difference in acoustic impedance) or external boundaries. When the reflected waves, or echoes, return to the surface, they produce displacements that are measured by a receiving transducer. If the transducer is placed close to the impact point, the response is dominated by P-wave echoes. The right hand side of figure 3-3 shows the pattern of surface displacements that would be occur. The large downward displacement at the beginning of the waveform is caused by the R-wave, and the series of repeating downward displacements of lower amplitude are due to the arrival of the P-wave as it undergoes multiple reflections between the surface and the internal void.

The impact-echo method was researched and developed at the National Institute of Standards and Technology. There is an ASTM Standard for concrete thickness determination.

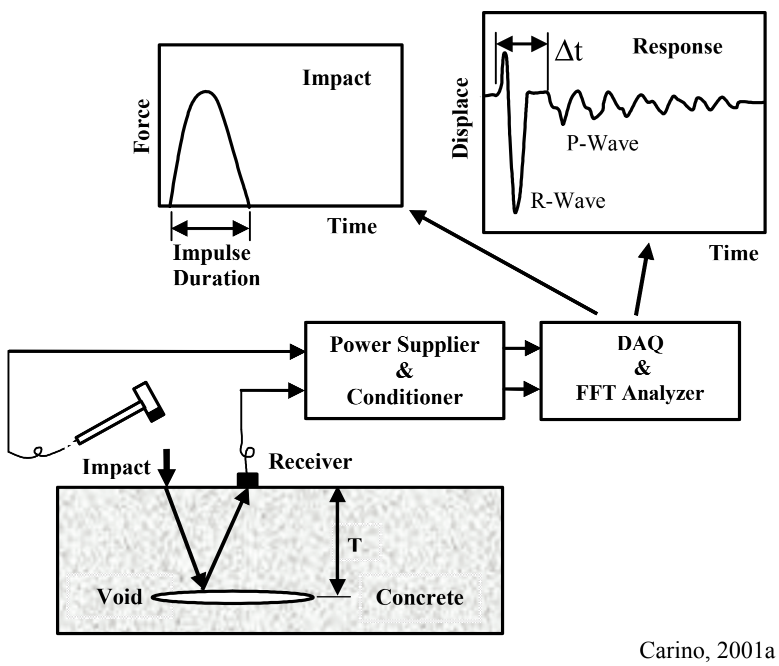


Figure 3-3. Setup for Impact-Echo Test

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[3] Steinbach and Vey, 1975; Lin et al., 1991, 1996; Carino, 2001a and b; Lin and Sansalone, 1996; Sansalone, 1997; Sansalone and Carino, 1988, 1989, 1991.

The impact-echo method has been successful in detecting a variety of defects, such as voids and honeycombed concrete in structural members, delaminations in bare and overlaid slabs, and voids in tendon ducts. Experimental studies have been supplemented with analytical studies to gain a better understanding of the propagation of transient waves in bounded solids with and without flaws. This method has also been extended to prismatic members, such as columns and beams, and applied to evaluate the quality of the bond between an overlay and base concrete (Lin and Sansalone, 1996; Lin et al., 1996).

3.4 Ultrasonic Method

Ultrasonic testing uses the transmission of high frequency sound waves into a material to detect defects within the material or changes in material properties (see figure 3-4). The most commonly used ultrasonic testing technique is pulse echo, wherein electronically controlled pulses are introduced into a material through a transducer. The ultrasonic energy then travels within the material, and reflections (echoes) are returned to a receiver from internal imperfections or from geometrical surfaces of the part. Based on controlled input and output signal, the ultrasonic pulse velocity can be measured or ultrasonic tomographic images can be established to detect the internal discontinuities and their locations[4].

Ultrasonic waves, which are generated by a piezoelectric transducer at frequencies above 20 kHz, propagate with a wavelength around 50-100 mm in concrete. This form of testing is used successfully at ultrasonic frequencies for the detection of flaws in metal castings and is the first nondestructive technique that was developed for the testing of concrete. However, it is much less practical in concrete and masonry, which have much higher attenuation characteristics and hence lower frequency signals are required to obtain a reasonable penetration. In addition, the numerous material boundaries in these materials result in scattering of both incident and reflected waves. Despite this fact, it has been successfully used for identifying and locating specific flaws in concrete and is also applicable to the investigation of small defects within masonry walls.

However, at present, the method is not commonly used for these purposes due to a number of technical difficulties. In the case of ultrasonic signals, the main factors to overcome are the need for good coupling of the transducer to the surface, which is often rough, and the scattering of the wave due to material heterogeneity. The need for effective coupling requires the use of a coupling agent, such as grease or petroleum jelly, to temporarily adhere the transmitter and receiver to the surface. This makes the process of moving the points of measurement quite slow and it is often difficult to achieve adequate coupling on some uneven surfaces. Scattering of the signal limits the propagation through the material and also leads to a complicated series of return signals. This makes it difficult to identify defects amongst the noise. In addition, surface waves, which travel more slowly than the compression waves, may arrive at the receiver within the same time interval and confuse interpretation. Further developments of the ultrasonic technique, for example improvements in signal generation, detection and data processing, are underway and may lead to a practical tool if the problems mentioned above are overcome.

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[4] Chang and Liu, 2003; McCann and Forde, 2001; Rens et al., 1997, 2005; Sack and Olson, 1995; Olson and Church, 1986; Martin et al., 1998; USACE 1998; Popovics, 2003; Kaiser and Karbhari 2001, 2002; Ciolko and Tabatabai, 1999

Olson, 2004

Figure 3-4. Ultrasonic Method to a Bridge Column

Currently available ultrasonic techniques do not have the capability to reliably detect cracks, and cannot accurately measure crack size and orientation because of unpredictable coupling between the ultrasonic contact transducer and the pin surface. To remove this unpredictability, the self compensating technique developed by Achenbach and Komsky has been applied to the inspection of pin connections. This technique makes it possible to determine crack size independently of the condition of the transducer to surface coupling.

3.5 Acoustic Emission (AE) Method

When a solid material is stressed, imperfections within the material may emit short bursts of energy called "emissions" or “events.” In much the same manner as ultrasonic testing, special receivers (sensors) can detect these acoustic emissions. The source of "emissions" can be evaluated through the study of their strength, frequency, dispersion, and location. The Acoustic Emission (AE) method has been applied to health monitoring of highway bridges for decades[4].

Acoustic emission signals cover a wide range of energy levels and frequencies but are usually considered to be of two basic types: burst and continuous. The term burst is a qualitative description of emission signals corresponding to individual emission events. The term continuous emission is a qualitative description for an apparently sustained signal level from rapidly occurring emission events. Emission frequencies range from below to well above the audible range for humans. However, most AE monitoring is accomplished in the kilohertz or low-megahertz range. Although emission is characterized as burst or continuous, signals of either type may propagate in any of the standard ultrasonic modes (i.e., shear, longitudinal, or surface waves). Furthermore, a single emission event can generate waves having more than one propagation mode.

A wide range of transducer types has been used to sense acoustic emission from materials, structures, and industrial equipment. The types of AE sensors include accelerometers, piezoelectric transducers, capacitive transducers, optical/laser sensors, microphones, strain gauges, etc.

The most widely used method of quantifying AE signals is the ring-down counting technique, which measures the characteristics of the emitted signal as its amplitude decays. For a typical sinusoidal AE pulse, an amplitude threshold is established for the acceptance of signals, and the number of signals exceeding this threshold is automatically counted by the instrumentation system. Signals crossing the threshold are usually plotted as a function of load, stress, time, or other parameters. They may be plotted as the count rate versus stress, or the plot may be of the total or cumulative count versus the selected parameter.

The AE method has wide applications. It can be used to monitor changing material conditions in real time and to determine the location of the emission centers as well. Typical applications include onsite monitoring of bridges and civil engineering structures. Simulated acoustic emission techniques are also useful for monitoring types of composite materials.

The advantages of AE are rooted in the basic characteristic where the active defect emits a signal that will find a path to the monitoring sensor location. Since it is a passive technique, no equipment is required to excite a pulse. Further, the received signals may be recorded for remote or delayed analysis and for storage. The requirements for equipment mounted on the monitored structure may be rather small. Other advantages are that AE techniques are highly sensitive to crack growth, and locations of growing cracks can be determined.

Additional advantages are the ability to monitor an entire system at the same time. With remote monitoring, the technique can be used in hostile environments. The item being tested usually can remain in operation during the process, and the entire volume of materials and structures can be inspected at a reasonable cost. It is also suitable for long-term in-service monitoring.

Disadvantages of the technique include the requirement of stress or other stimuli to generate the acoustic emission event. Therefore, stabilized cracks cannot be detected with emission techniques. The size of cracks or other defects cannot be precisely determined. Some materials and certain tempers of other materials are not very emissive and are unsuitable for monitoring. Electrical interference and ambient noise must be filtered out of emission signals. Also, the multiple numbers of travel paths from the source to the sensor in complex structures can make signal identification difficult.

AE techniques were used in the 1970s to monitor some bridges. In the 1980s, extensive studies were carried out to use acoustic emission techniques for bridge inspections.

3.6 Vibration (Modal Analysis) Method

The basic principle of vibration method is that modal parameters such as natural frequencies, modal shapes, and modal damping are functions of the physical properties (mass, stiffness and damping). Theoretically, the global deterioration, discontinuities, cracks and other variations in structural properties will alter physical properties, and then the modal parameters of the structures. The modal parameters themselves or their combination can be used as detection and evaluation for bridge condition assessment and monitoring systems. The dynamic vibration tests are carried out by applying known/controlled excitations (such as hammer impulse forces) to the structure or based on ambient excitations (such as vibration introduced by traffic). From the recorded vibration responses, the modal parameters and indicators can be extracted using a digital dynamic signal processing and system identification system[5].

Modal analysis is a tool that has been developed over many years as a method to determine the characteristics of a structure. To obtain the parameters, a series of tests are carried out on the structure. Accelerometers are fixed to locations on the structure and response data are gathered after the structure is excited. There are two approaches to modal bridge excitations. The first is forced vibration excitation. This procedure requires the excitation of the structure using either a shake or an instrumental hammer. On a large heavily damped structure, it is clearly impractical to expect to obtain the modes of vibration of the structure using an instrumental hammer; however, the addition of major shaker may, in itself, modify the modes of vibration. The alternative procedure is ambient vibration testing, whereby the modes of vibration are excited by either wind or traffic loadings. There is clearly less control over the response of the structure using this procedure. In terms of day-to-day bridge reliability evaluation, modal testing is expensive and can only be sensibly applied to bridges which are relatively uniform in their behavior. Considerable anisotropy in the behavior of the structure means that the small changes in the frequency of the mode shape and the level of damping may prove difficult to analyze. Likewise, temperature effects from one signature analysis to another may prove equally difficult to interpret.

The basic premise of vibration-based damage detection is that damage will significantly alter the stiffness, mass or energy dissipation properties of a system, which, in turn, alter the measured dynamic response of that system. Although the basis for vibration-based damage detection appears intuitive, its actual application poses many significant technical challenges. The most fundamental challenge is the fact that damage is typically a local phenomenon and may not significantly influence the lower frequency global response of structures that is normally measured during vibration tests. Stated another way, this fundamental challenge is similar to that in many engineering fields where the ability to capture the system response on widely varying length scales has proven difficult. Another fundamental challenge is that in many situations, vibration-based damage detection must be performed in an unsupervised learning mode. Here,

[5] Chang and Liu, 2003; McCann and Forde, 2001; Rens et al., 1997, 2005; Sack and Olson, 1995; Olson and Church, 1986; Martin et al., 1998; USACE 1998; Popovics, 2003; Kaiser and Karbhari 2001, 2002; Ciolko and Tabatabai, 1999; Sansalone and Carino, 1988; Feng and Kim, 1998; Feng et al., 2004; Luscher et al., 2001; Farrar et al., 1999, 2000; Sohn and Law, 2000; Sohn et al., 1999; Doebling and Farrar, 1996, 1998.; Farrar and Jauregui, 1996, 1998a and b; Farrar and Doebling, 1997a and b; Doebling et al., 1996, 1997a and b; Liang and Lee, 1991, 2005; Kong et al., 1996 a and b

the term unsupervised learning implies that data from damaged systems are not available. These challenges are supplemented by many practical issues associated with making accurate and repeatable vibration measurements at a limited number of locations on complex structures often operating in adverse environments.

The University of Connecticut research team (Sansalone and Carino, 1988) used a small-scale bridge model and placed accelerometers along the bridge spans. Mock vehicles were driven over the bridge and a series of tests were performed before vibration signature analysis to detect structural degradations could be performed. Tests were performed to see how vehicle velocity, roadway roughness, and vehicle mass affect structural dynamic parameters. The test results show that the modal parameters are consistent with the baseline verification study case and the vibration signature monitoring program is effective in determining structural degradation.

The most extensive field application of vibration signature analysis has been performed at Los Alamos National Laboratory (LANL)[6] LANL started vibration-based damage detection work 15 years ago. Most of the work conducted at LANL in this area has focused on applications to civil engineering infrastructure. Analysis of data sets from modal tests of bridges has demonstrated the importance of quantifying the variability of the measured modal parameters resulting from environmental conditions. Statistical analysis techniques such as Monte Carlo simulation and Bootstrap analysis have played an important role in the quantification of such variability. Ongoing work is focused on the testing of idealized structures for the purposes of comparing the effectiveness and limitations of various damage ID techniques. As one of their major contributions, a MATLAB-based computer code known as DIAMOND for statistical modal analysis, damage detection, and finite element model refinement has been developed. The damage detection algorithms and computer codes have been successfully applied to the I-40 bridges over the Rio Grande in Albuquerque, New Mexico and Alamosa Canyon Bridge in southern New Mexico. Especially, since the I-40 bridges were to be demolished and replaced, the investigators were able to introduce simulated cracks into the structure, perform vibration tests before and after each level of damage had been introduced, and then use the test data to validate various damage ID methods. Damage detection algorithms were applied to these data and to numerical data from finite element simulations of the I-40 bridge tests where other damage scenarios were investigated.

Furthermore, in cooperation with the University of California, Irvine, staff from LANL performed numerous experimental modal analyses on the seismically retrofitted, reinforced-concrete bridge columns. These modal tests were performed at stages during the static load cycle testing when various amounts of damage had been accumulated in the columns. These tests and the associated data obtained will be used to demonstrate a statistical pattern recognition process of vibration-based damage detection. Figures 3-5 through 3-7 show the use of the modal analysis method in the field and flowcharts of the damage identification module based on modal analysis, respectively.

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[6] Luscher et al., 2001; Farrar et al., 1999, 2000; Sohn and Law, 2000; Sohn et al., 1999; Doebling and Farrar, 1996, 1998.; Farrar and Jauregui, 1996, 1998a and b; Farrar and Doebling, 1997a and b; Doebling et al., 1996, 1997a and b; Liang and Lee, 1991, 2005; Kong et al., 1996 a and b

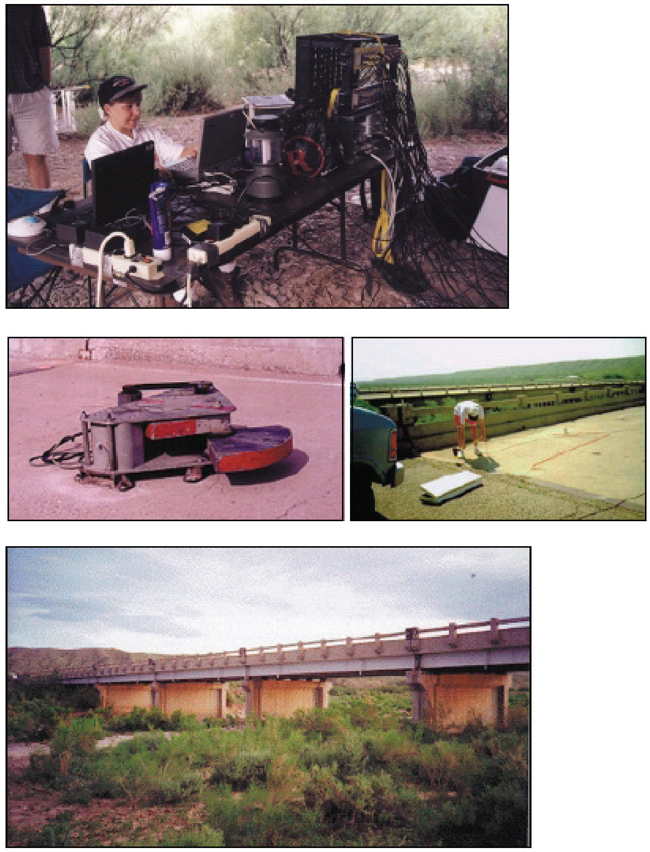


Figure 3-5. Health Monitoring and Damage Detection for Alamosa Canyon and I-40 Bridges Carried out by Los Alamos National Laboratory

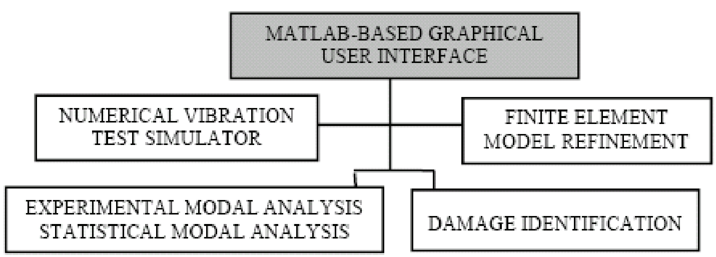
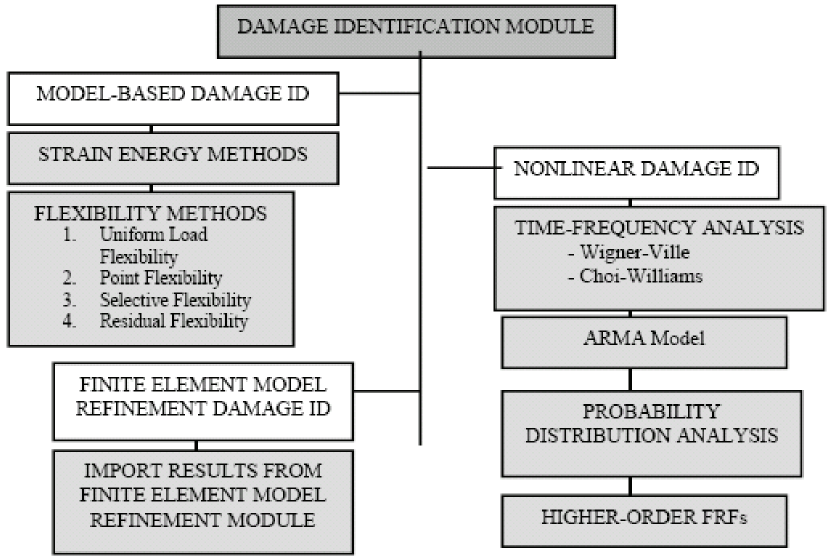


Figure 3-6. Flowchart of the Top Level of DIAMOND



Los Alamos National Laboratory

Figure 3-7. Flowchart of Damage Identification Module Based on Modal Analysis

A further development of vibration testing is not limited to conventional modal parameters. This is because the conventional model parameter, namely the natural frequencies, damping ratios and mode shapes, are not very sensitive to column damage. For example, if a certain type of damage occurs that reduces the overall stiffness by 1%, which is often considered to be a significant change in column stiffness, then the corresponding change in natural frequency is only about 0.5%. At the same time, it is reported that the change in natural frequency due to the environmental temperature may easily cause the change in natural frequency to be more than 1%. In this case, the measurement signal-to-noise ratio is obviously less than one.

To overcome this problem, damage indicators can be the combination functions of the conventional parameters. Furthermore, they can be other vibration-related quantities. Liang and Lee suggested a new model parameter called the modal energy transfer ratio (ETR) (Liang and Lee, 1991). This parameter can have a better measurement signal-to-noise ratio (Kong et al., 1996a and b). Due to the complication of the numerical computation to extract the ETR, a newly suggested parameter called dynamic reciprocal parameter (DRP) is further studied by Liang and Lee (Liang and Lee, 2005). Furthermore, based on the same concept of modal energy, the model energy integration ratio (EIR) is found to be more stable to extract and is sufficiently sensitive to the physical change of a system. Figure 3-8 shows the sensor installation and testing sites for two bridges in the Buffalo, New York area.

Figure 3-8. (a) Sensor Installation Site for Condition Monitoring of the Intersection Bridge between the 990 Expressway and Sweet Home Rd., Amherst, New York; and (b) Data Collection Site of the Intersection Bridge between NY Highway 263 and Bikeway, Amherst, New York

3.7 Microwave/Ground Penetrating Radar (GPR) Method

Microwave and millimeter wave inspection techniques involve the propagation of electromagnetic waves from probes (typically antennas) at frequencies ranging from 300 MHz to 300 GHz in dielectric (i.e., electrically insulating) materials. Separate transmitting and receiving probes may be employed through transmission techniques, or a single probe may be used for transmitting and receiving reflected wave energy. The term ‘‘ground penetrating radar’’ is often used to describe reflected wave techniques that employ a single transmitting/receiving antenna (Chang and Liu, 2003).

Pulse mode ground-penetrating radar (GPR) systems radiate short pulses of high frequency electromagnetic energy into the ground from a transmitting antenna. The propagation of the radar signal depends on the frequency-dependent dielectric properties of the ground. When the radiated energy encounters an inhomogeneity in the electrical properties of the subsurface, part of the incident energy is reflected back to the radar antenna. Reflected signals are amplified, recorded, and processed. From the recorded display, subsurface features such as soil/soil, soil/rock, and unsaturated/saturated interfaces can be identified. In addition, the location of buried cables, pipes, drums, and tanks can be detected.

Electrical conductivity of the soil or rock materials along the propagation paths introduces significant absorptive losses that limit the depth of penetration. The radar frequency selected for a particular study is chosen to provide an acceptable compromise between deeper penetration and higher resolution. High frequency radar signals produce greater resolution, but are more limited in depth of penetration. To obtain accurate information on the depth of signal response, GPR has to be calibrated with a core sample.

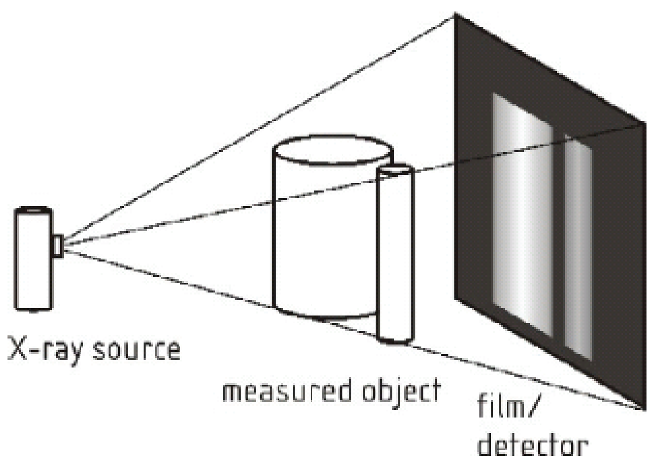
Existing GPRs for pavement subsurface measurements are bulky and expensive. Recent research has been toward making more compact and lower cost GPRs by using microwave technology and millimeter-wave frequencies (.30 GHz), which use microwave integrated circuits for pavement surface mapping.

The step-frequency GPR sensor transmits sequences of sinusoidal signals of different frequencies toward targets, receives return signals from the targets, and processes the return signals. In each sequence, the frequency is shifted in discrete values—each value is held constant for a period of time and then changed to the next higher value. The received signals at step frequencies, reflected from the targets, are down converted into an intermediate frequency (IF) signal. This IF signal is then demodulated into in-phase (I) and quadrature-phase (Q) signals in the base band. The I and Q signals represent both the amplitude and phase information of the targets, from which target signature can be determined.

The millimeter-wave interferometer surface-profiling sensors transmit a millimeter-wave signal to illuminate a surface via the antenna. The return signal from the surface is captured by the sensor via the antenna and converted into a base-band signal, which is then processed to produce the surface profile. This surface profiling is based on a phase-detection process, in which the phase change of the return signal due to surface profile is detected and this phase information is processed using the phase unwrapping signal-processing technique. The reconstructed phase is then used to reconstruct the surface profile.

3.8 Radiography Method

The method of radiography utilizes very short wavelength electromagnetic radiation, namely X-rays, gamma-rays as an energy source which will penetrate the concrete to examine parts and products for flaws. An X-ray machine or radioactive isotope is used as a source of radiation which will be partially absorbed by the medium. The amount of absorption that will occur is dependent upon the density and thickness of the material that the radiation is passing through, and also the characteristics of the radiation. The radiation which passes through the material is directed through a part onto a film or an electronic device (plate). When the film or plate is processed, a negative-like picture is obtained that shows the internal characteristics of a part (see Figure 3-9). Possible imperfections show up as density changes in the film, in much the same way as an x-ray can show broken bones (McCann and Forde, 2001).



Saleh, 2004

Figure 3-9. Principles of Radiography

Radiography is capable of detecting any feature in a component or structure provided that there are sufficient differences in thickness or density within the test piece. Large differences are more readily detected than small differences. The main types of defect, which can be distinguished, are porosity and other voids and inclusions where the density of the inclusion differs from that of the basic material. Generally speaking, the best results would be obtained when the defect is an appreciable thickness in a direction parallel to the radiation beam. Plain defects such as cracks are not always detectable and the ability to locate a crack will depend upon its orientation to the beam. The sensitivity possible in radiography depends on many factors but generally if a feature causes a change in absorption of 2% or more compared to the surrounding material, then it will be detectable.

Radiographic techniques are frequently used to check welds and castings and in many instances, radiography is specified for the inspection of components.

X-rays require an instrumentation system employing an electrically powered linear accelerator to generate X-rays. As will be appreciated from the medical use of X-rays, significant precautions need to be taken with regard to the use of personnel in the vicinity of an X-ray. Thus, when having an X-ray undertaken upon a patient, one has to wear a lead protective apron. These precautions are for low powered X-rays which are adequate for checking fractures or bone structure shapes such as the spine and only low doses of radiation are necessary. However, in electrically "lossy" materials such as concrete, much higher doses of X-ray are required to be effective and thus safety becomes a paramount issue. Higher dosages of X-ray can be used where the component can be put into a sealed container as occurs when baggage is x-rayed at an airport, but a construction site is a totally different application. A specialist and potentially cost effective application of radiography includes checking for voiding in post-tensioned bridge structures. The instrumentation system used in this instance is the French "Scorpion System," but the very high dosage of X-rays means that an exclusion zone up to a 1000 m may need to be cleared of human beings and cattle. However, the advantage is that the Scorpion system with high powered X-rays gives an instant view of the inside of a post-tensioned bridge duct on a television monitor, which is then video recorded for future analysis.

Gamma-rays involve a nuclear source and require the nuclear probe to be brought into contact or into a hole drilled in the structure. This technique is less potentially dangerous than X-rays provided that the nuclear source is carefully controlled. However, the gamma-ray procedure emits far less power than the X-ray system and the images tend to be weaker and require longer "stacking" time. Thus, a survey which might take 30 minutes using a high powered X-ray would take several hours using a gamma-ray procedure.

In terms of safety, if something goes wrong, the X-ray can be switched off as it is an electrically generated system. However, the gamma-ray system cannot be switched off as it is a nuclear source. Additionally, the gamma-ray source cannot be carried in a conventional motorcar without special facilities of a lined and protected box and various warning signs on the vehicle. Additionally, the vehicle cannot be randomly parked at, for example, service stations on motorways and so on. Special licenses have to be obtained for the carriage and use of gamma-ray sources. There are also limitations upon the health of workers exposed to gamma-rays and people who are particularly vulnerable due to health problems or pregnancy.

3.9 Infrared (IR) Thermography Method

Infrared thermographic testing techniques are based on the fundamental principle that subsurface defects in a material affect heat flow through that material, which will cause localized differentials in surface temperature. Discontinuities, such as the delaminations, interrupt the heat transfer through the concrete. In periods of heating, the surface temperature of delaminated areas is higher than the temperature of the surrounding concrete. Sensitive infrared systems (such as the one shown in figure 3-10) are used to detect the differences in the surface temperatures. Through the analysis of the temperature on the surface, the presence and location of any subsurface defects can be identified[7].

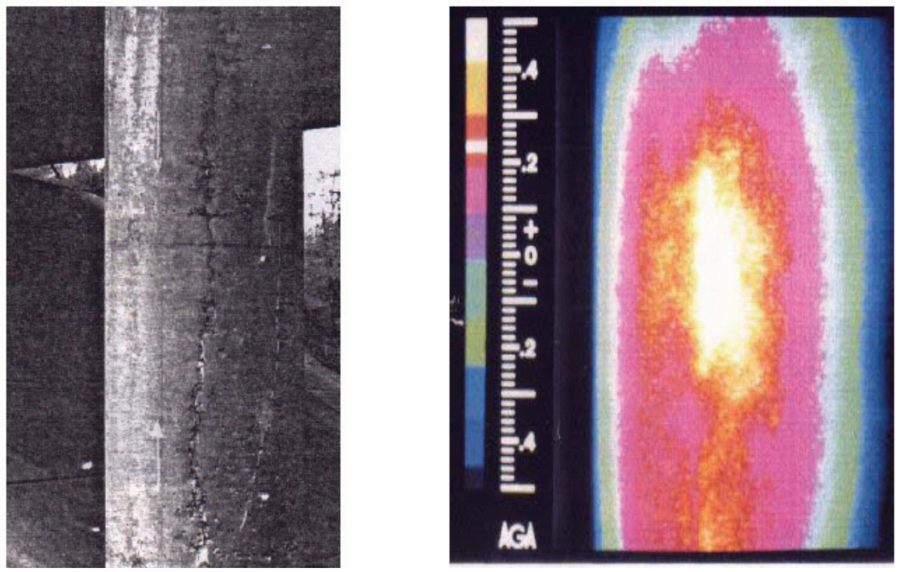
Duke, 2004

Figure 3-10. Infrared Thermal Imaging Systems

Thermography uses high-speed and highly-sensitive infrared imaging for detecting temperature differences. This instrumentation has been widely used in electrical work for detecting hot spots in electrical equipment which indicate shorts or other electrical problems. Recently, this equipment has been applied to mechanical equipment and civil infrastructures. Thermography may not be useful in identifying the root cause of a failure after it happens, but it could possibly be used to identify a potential problem before it fails, which is much more desirable. Thermography can potentially provide an effective method to monitor concrete material stress-strain behavior during fatigue because of the temperature differences being generated. In the 1960's, researchers developed the theory that directly relates the temperature within the material internal stress-strain state, which in turn controls the mechanical and fatigue behavior of the material. It was not until the 1980's that thermographic equipment was developed which could be used to detect these minute temperature differences. Recent research has shown the potential of thermography in monitoring mechanical damage (see figure 3-11). More detailed

[7] Chang and Liu, 2003; McCann and Forde, 2001; Rens et al., 1997, 2005; Sack and Olson, 1995; Olson and Church, 1986; Martin et al., 1998; USACE 1998; Popovics, 2003; Kaiser and Karbhari 2001, 2002; Ciolko and Tabatabai, 1999; Duke, 2004

investigations and comprehensive analysis are still needed to develop a more practical thermography method for characterizing the structural defects. However, this method may hold promise for future investigations.



Duke, 2004

Figure 3-11. Infrared Image of Rebar Corrosion Induced Delamination of a Bridge Column

3.10 Other Methods

Many other NDT/NDE techniques, such as eddy current, magnetic flux, polarization resistance, Bragg grating, cover meter, shearography, laser scanner, surface hardness methods, etc., are used to inspect and assess highway bridges. However, they have particular attributes that make them useful for specific situations and purpose that are not applicable to FRP-jacketed bridge columns. Examples include the eddy current method, which is commonly used for metallic material flaw detection in bridges.

CHAPTER 4
BRIEF EVALUATION OF NDT/NDE METHODS CURRENTLY USED FOR FRP-JACKETED COLUMNS OF HIGHWAY BRIDGES

4.1 Vibration Method

Feng and Bahng (1999) developed a method to assess damage in jacketed columns by taking advantage of the change in the bridge vibration characteristics, including the natural frequencies and mode shapes before and after damage. They experimentally and analytically developed a fundamental knowledge base to correlate vibrational characteristics and damage described by stiffness degradation of jacketed columns. A back-propagation neural network technique was employed to identify the extent and location of damage represented by stiffness reduction, without expensive and cumbersome search processes, as required in a conventional system identification.

In their study, damage assessment is concentrated on the column/footing system. The authors built half-scale bridge columns with footings, wrapped them with the composite jackets, and performed cyclic loading tests using a hydraulic actuator fixed on a strong wall to introduce different levels of damage to the columns. On the other hand, vibration tests using an electric shaker were performed on the columns, before and after jacketing and under undamaged, moderately damaged (ductility 2), and severely damaged (ductility 7) conditions. Based on the acceleration response measurements from the vibration tests, the natural frequencies and mode shapes of the columns under those conditions were obtained. Meanwhile, finite-element models were developed for the column/footing systems, in which the support between the footing and the strong floor was modeled by a torsional spring. The neural network system identification technique was used, the increase in stiffness due to the composite jackets was identified, and the damage by the cyclic loading was assessed.

In the experimental study, two half-scale bridge columns of 610 mm (24 in.) diameter and 3.657 m (12 ft) height were built and tested, which represent the existing California bridge columns designed using older (pre-1971) specifications.

In order to compensate for the insufficient lap splice length and reinforcement confinement, one of the columns was retrofitted with glass fiber composite jackets, and the other with carbon fiber jackets, as shown in Figure 4-1. A vertical gap of 25.4 mm (1 in.) was provided between the jacket and footing to prevent the damage from penetrating into the footing. In the cyclic loading tests, a reasonable constant axial load was applied on the column through two tensioned rods, while cyclic horizontal loads were applied on top of the column by an actuator fixed on the strong wall. Up to a ductility factor of 3, no apparent damage was observed on the jackets or columns by visual inspection. At a ductility factor of 7, severe failure occurred at the lap splice region for both columns, significantly decreasing the load capacity of the columns. Crushed concrete was observed in the 25.4 mm (1 in.) gap areas of the columns, while no cracks were visible on the jackets and other parts of the columns.

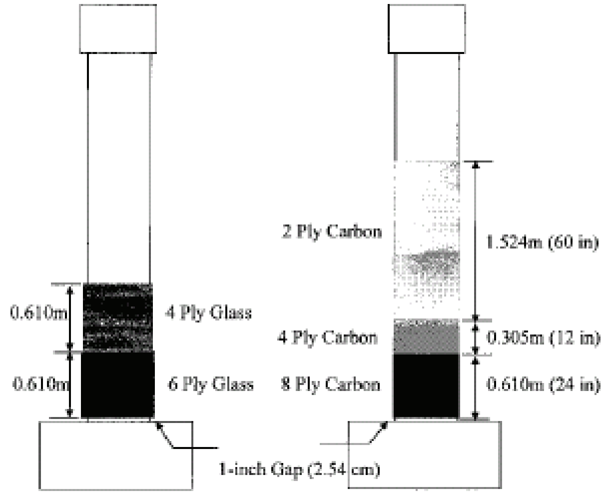


Figure 4-1. Jackets for Test Columns

Vibration tests using a shaker were also performed on these two columns. The constant axial load was removed from the columns, while vibration tests were performed. For the glass fiber jacketed column, unjacketed, jacketed/undamaged, and jacketed/damaged cases were studied, while for the carbon fiber-jacketed column, jacketed/undamaged, moderately damaged (ductility = 2) and severely damaged (ductility = 7) cases were studied. The experiments involved exciting each column using an electro-dynamic shaker by a swept sinusoidal signal. For all cases, modal parameters (natural frequencies and mode shapes) were identified as system identification fundamental databases. Locations of the accelerometers and shaker for glass fiber-jacketed column used in the tests are shown in Figure 4-2. It was noticed by the authors that the measurable shifts in the frequencies for jacketing and damage were clearly demonstrated. Especially at ductility 2 where no damage was observed by visual inspection, the frequencies of the column clearly changed.

In the system identification and damage assessment part, the authors employed a back-propagation neural network approach to solve the system identification inverse problem. The unjacketed test column was modeled by the finite-element model, and the corresponding structural baseline parameters were calculated and updated using the neural network system identification technique to reduce the difference between the computed and measured data. Through estimating and comparing correction coefficients of the element stiffness matrices, structural damage to the jacketed/undamaged, jacketed/ moderately damaged and jacketed/severely damaged cases, the severity of columns were successfully assessed. However, the damage was not observed in the 25.4 mm gap of the column (moderate damage) and in the jacketed column parts (severe damage) by visual inspection.

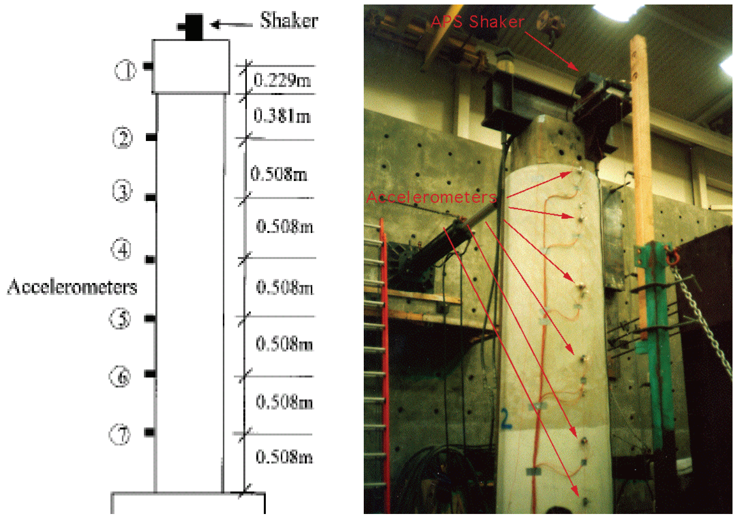


Figure 4-2. Locations of Accelerometers and Shaker for Glass Fiber-Jacketed Column Test

Although the present study focused on jacketed columns without considering the bridge superstructure, it provided some valuable information for dealing with the reality that requires the vibration test on the entire bridge for assessing the damage in the jacketed columns. In order to apply the proposed approach in the field, the undamaged bridge must be excited horizontally and the modal analysis must be performed on the finite-element model of the bridge to establish the baseline values of bending and shear stiffness of each element. The same vibration test must be performed after an earthquake to identify the change in each element stiffness coefficient, which represents the extent of the damage at the element. Modeling techniques must be developed to minimize the modeling errors arising from the soil effects on the footings and abutments. In addition, the effect of the column axial loads due to the superstructure on the vibration characteristics must be studied. All these important issues related to the application of the proposed approach in the field are the subjects of a future study. Some additional observations are:

- Global structural modeling for bridge columns is needed for both experimental and analytical approaches.
- The damage index (correction coefficients) may be insensitive to local void and debonding between the jacket and the column.
- The reliability of the damage assessment depends on the accuracy of modeling, which may be greatly affected by boundary conditions of the column, such as the connection to the superstructure and soil effects on the footings and abutments.
- The method is difficult and inconvenient for application in the field; e.g., structural excitation with electro-dynamic shaker.

4.2 Microwave-based (Electromagnetic, Radiographic) Method

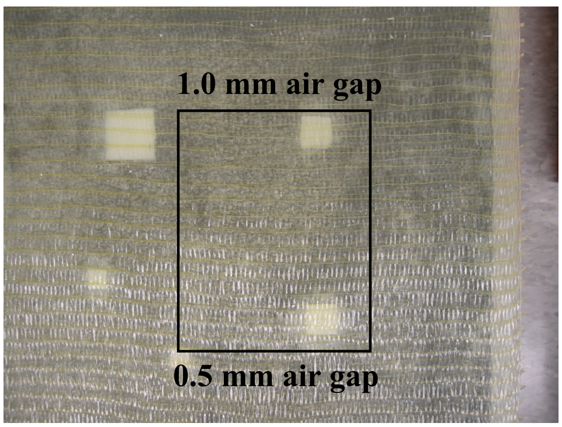
4.2.1 Electromagnetic Imaging Technology

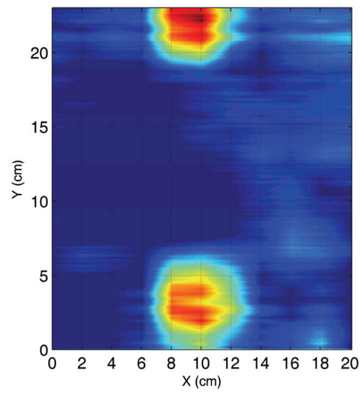
Feng and colleagues (University of California, Irvine) developed an electromagnetic (EM) imaging technology for detecting damage of FRP-wrapped concrete columns such as voids and debonding between the jacket and the column (Feng et al., 2000a and b, 2002: Kim et al., 2001a and b, 2003, 2004). This technology is based on the reflection analysis of a continuous EM wave sent toward and reflected from the layered FRP-adhesive-concrete medium: voids and debonding areas will generate air gaps that produce additional reflections of the EM wave. In their study, the computer simulation demonstrated the difficulty in detecting damage by using plane waves, as the reflection contribution from the voids and debonding is very small compared to that from the FRP-wrapped column. In order to alleviate this difficulty, two types of focusing techniques were developed, one using dielectric lenses and the other array antennas. The former is referred to as a passive system as the focusing point has to be manually adjusted by moving the lenses, while the latter is an active system in the sense that focusing is automatically performed by sophisticated software without moving the antenna arrays. Both systems have demonstrated their effectiveness in detecting debonds and voids in FRP-wrapped concrete structures and voids inside concrete.

Recently, the EM imaging technology has been commercialized into hand-held real-time debond detectors through Newport Sensors, Inc. These products are specialized in detecting invisible air voids and debonds between FRP and concrete or between layers of FRP composites. As a structural surface being scanned by the hand-held unit, the subsurface image is displayed on a computer screen in real-time. A debond as small as 10 mm x 10 mm x 0.25 mm (Depth) is detectable. Figure 4-3 shows the inspection of FRP-wrapped bridge columns in the Yolo Causeway Viaduct, Sacramento, CA. Figure 4-4 shows a scanned subsurface image that clearly indicates two debonding areas on an FRP-wrapped concrete specimen: one has an air gap of 1.0 mm and the other 0.5 mm. The subsurface image agrees well with the reality where the two debonding areas were artificially created with known dimensions. Such unique features as the hand-held portability and real-time results make the debonds detector products highly suited for in-situ inspection of FRP-wrapped concrete structures for quality control/assurance, as well as post-event damage assessment and long-term performance monitoring.

Figure 4-3. Hand-Held Debond Detector for Inspection of FRP-Wrapped Concrete Structure

(a) Debond Detector with Automatic Scanning Feature





(b) Scanned Area on FRP-Wrapped Concrete (c) Real-Time Image Indicating Debonds

Figure 4-4. Scanned Subsurface Image

4.2.2 Near-Field Microwave NDT Techniques

Akuthota and Hughes et al. (University of Missouri-Rolla, Rolla) applied near-field microwave NDT techniques, utilizing open-ended rectangular waveguides to detect debonding in a specially prepared CFRP reinforced mortar sample (Akuthota et al., 2004; Hughes et al., 2001; Stephen et al., 2004). The experimental results show the capability of this technique for verifying repair quality.

Near-field microwave nondestructive testing (NDT) techniques, using open-ended rectangular waveguide probes, have been extensively used in the past decade for detecting disbands and delaminations in complex stratified composite structures. These techniques are capable of detecting a thin disbond, evaluating its spatial extent and its severity (i.e., relative thickness). Near-field microwave NDT techniques, using open-ended rectangular waveguides for the purpose of disbonding detection and evaluation, possess the following important advantageous features:

1. Measurements are conducted in a non-contact and one-sided manner.
2. The standoff distance (e.g., the distance between the probe and the structure under test) can be optimally chosen to increase the overall sensitivity of the method.

3. The method provides for high level of measurement sensitivity (i.e., detecting thin disbonds) while providing for a relatively fine spatial resolution.
4. Measurement results are obtained rapidly and in real-time while the measurements are conducted on-site and with minimal required surface preparation.
5. The measurement system can be constructed to be small in size, handheld, easily portable, battery operated, rugged, and robust.
6. Line scans as well as microwave images (i.e., raster scans) of a disbonded region can be quickly produced.
7. Minimal operator expertise is required.
8. The measurement system is inexpensive, requires at low microwave power levels, and is not source of electromagnetic interference.

The earlier works carried out by Hughes et al. have also shown the potential of this technique for detecting simulated disbonds in externally bonded carbon FRP laminates in reinforced cement–paste samples (Hughes et al., 2001). The results of this investigation clearly showed the ability of this technique to detect disbonds with different thicknesses, spatial extents, and shapes. The results also confirmed that the disbonds could be detected at a relatively wide range of standoff distances. This is an important fact since it indicates the practical robustness of the method. The current investigation presented here shows the experimental results of detecting actual disbands (i.e., air gap) in a specially prepared CFRP reinforced mortar specimen and the potential for evaluating the quality of repair by epoxy injection.

Figure 4-5 shows the schematic of a near-field microwave measurement system employing an open-ended rectangular waveguide probe. A microwave signal, at a specific frequency and standoff distance, is transmitted via the probe and interacts with the composite structure under inspection. A portion of this signal is then reflected by the composite structure and is picked up by the probe. Subsequently, the magnitude and phase of the reflected signal may be compared to that of the incident signal. Depending on the type of comparison made (i.e., phase and/or magnitude) and the microwave detection approach used, a dc output voltage can result from this comparison which is then plotted as a function of the locations scanned by the probe. One simple detection approach involves monitoring the standing wave pattern inside of the waveguide probe as a function of scanning location. This approach was used in their investigations.

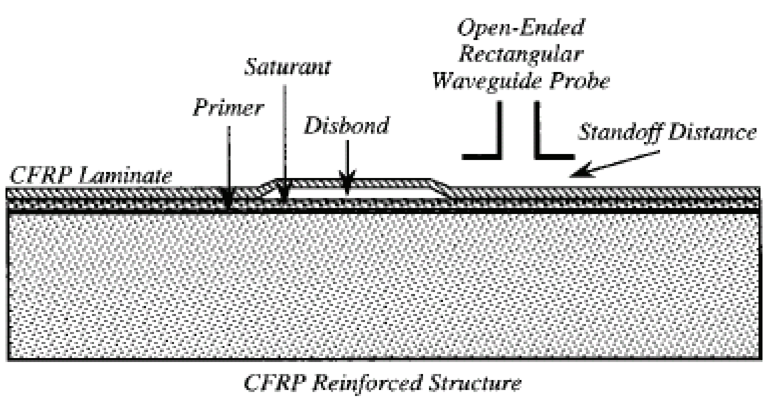


Figure 4-5. Schematic of Microwave Measurement Approach

Figure 4-6 shows the finished sample, with the manufactured disbonds outlined in thick solid lines and the smaller unintentional disbonds outlined in thin dotted lines. Figure 4-7(a) and (b) show sample images that resulted from the testing. All results demonstrate the effectiveness of the near-field microwave nondestructive testing method using open-ended rectangular waveguide probes.

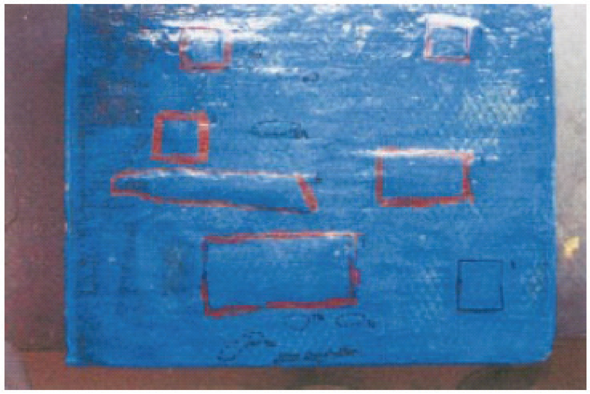
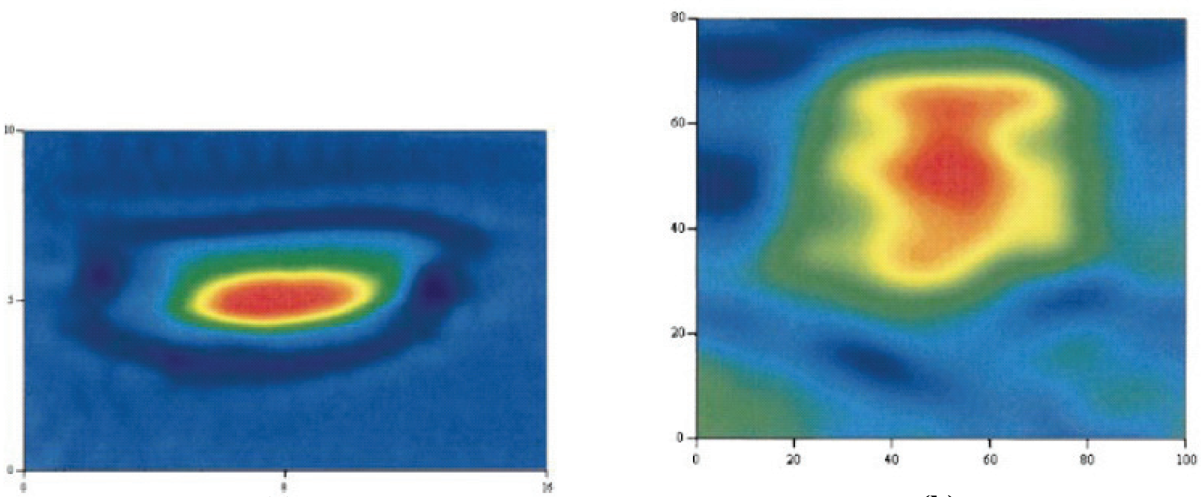


Figure 4-6. Top View of Carbon Fiber Reinforced Polymer Laminate Adhered to Mortar Substrate (Sample) with Disbonded Regions Produced by Injecting Air in between Laminate and Substrate



(a) **(b)**

Figure 4-7. (a) Microwave Image of Disbond at Frequency of 24 GHz and Standoff Distance of 7 mm; (b) Microwave Image of Square-shaped Disbond at Frequency of 10 GHz and Standoff Distance of 1.5 mm using Orthogonal Polarization (dimensions in millimeters)

Investigations performed at 10 and 24 GHz clearly showed that the disbonds including several subtle unintentional disbonds were easily detected using this technique. Disbonded regions as small as 2 cm by 0.5 cm were detected, which is usually much smaller than the critical size of interest in practice. Standoff distance variation, in the range of a few millimeters, had no adverse effect at 10 GHz (X-band), and minimal effect at 24 GHz (K-band). The presence of excess epoxy was not sufficiently detectable at 10 GHz. However, excess epoxy was detected at 24 GHz which was also discernable from a disbond. Important dimensional information such as spatial extent, location, and the geometry of a disbonded region was readily provided by this method. Furthermore, the potential of using this technique for evaluating the quality of repair of a disbonded region by epoxy injection was also demonstrated.

While manufacturing the disbonds, several subtle and unintentional disbonds were also generated. These disbonded regions were smaller than the intentional ones. Nevertheless, they were readily detected without a priori knowledge of their existence. The presence of these unintentional disbonds was later verified using tap testing. Detection of disbonds which are less severe in thickness and spatial extent than the critical size (such being these unintentional disbonds) clearly demonstrates the robustness of this near-field microwave NDT technique. Detecting such defects leads to the temporal study of disbonds as it relates to observing the changes in a disbonded region over time.

A mortar substrate devoid of large aggregate was used in this investigation. When concrete substrates are used, one might expect some signal to be scattered by the individual aggregate. This may reduce the sensitivity of the method. However, this is not a major issue since using higher frequencies and in particular lower incident microwave power limits the penetration of the signal into the sample and can significantly reduce any problems associated with this fact. Another related issue is the presence of reinforcing steel bars in concrete structures. Even though the microwave signal is not expected to penetrate to the rebars, the same remedy mentioned above will alleviate any such concern.

The method described in their papers has the potential for providing quantitative information about a disbonded region. The information provided by this method includes the spatial extent of a disbonded region (and its shape) as well as the thickness of the disbond (i.e., severity). The former information is directly and closely indicated by the images provided, since production of high spatial resolution images is one of the major attributes of this near-field measurement. The latter information is not directly provided and one of two simple methods may be incorporated into the measurement technique to provide this information. The first method involves an experimental calibration of the system, by which the response to several known disbond (i.e., “calibration standard”) thicknesses may be obtained first and then the response to a disbond with an unknown thickness may be compared to the calibration standard to obtain the unknown disbond thickness. This calibration method requires that several calibration standards with the expected disbond thicknesses be prepared and carefully tested. The second method involves the utilization of the multilayer electromagnetic formulation by which the expected response of the system to disbonds with various thicknesses can be a priori evaluated. Subsequently, the measured response for an unknown disbond may be compared with the electromagnetic formulation results to obtain the unknown disbond thickness.

Although the satisfied results have been obtained, the researchers declared that the technique needs to be further developed as a low cost, easy to use, easily portable, rapid, and real-time automated system for detecting disbonds in CFRP strengthened structures.

4.3 Infrared Thermography Method

D.R. Jackson and colleagues (Federal Lands Division, FHWA) (Jackson et al., 1999) has applied the IR method to some FRP retrofitted RC columns on a bridge structure in Owego, NY. They found that the IR system could easily pick up debonding and blistering between the FRP and the RC after FRP wrapped surfaces were heated up by a portable propane heater. The results were confirmed with hammer sounding (impact-echo) method. They also found that the thermal variation of debonding has a different signature than that of a delamination, and therefore can be identified. The size of delamination and debonding flaws from IR data can be achieved through computerized image processing techniques.

Monica A. Starnes and colleagues (Dept. of Civil and Environmental Engineering, Massachusetts Institute of Technology and Building and Fire Research Laboratory, NIST) also applied the infrared thermography method to detect near-surface defects and quality control of concrete structures strengthened with FRP successfully (Starnes et al., 2003). Their study involved both experimental measurements and numerical simulations of infrared thermography testing of FRP laminates applied to concrete. Figure 4-8 shows thermogram of test object during qualitative detection of simulated subsurface flaws.

A controlled-flaw specimen was used to study the response of different materials used to simulate flaws at the interface of the FRP laminate and concrete substrate. The results showed that all simulated flaws could be detected, and that the low-conductivity fabric material gave a response similar to that of an air void. An experimental system was developed to allow measurement and control of the heat pulse. This was necessary to allow for a comparison of measured thermal response parameters with those computed using numerical models.

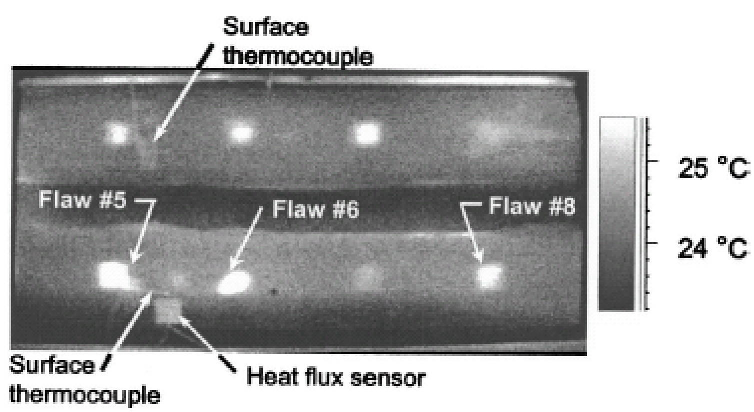


Figure 4-8. Thermogram of Test Object During Qualitative Detection of Simulated Subsurface Flaws

Numerical simulations were performed using 2D models of the controlled-flaw specimen. Figure 4-9 shows the test object used in finite-element. Three cases were simulated to represent different levels of convective cooling of the surface. The measured thermal responses associated with the air void were compared with the analytical results. It was found that the amount of convective cooling had a minor effect on the maximum signal and the time to reach the maximum signal. The good agreement between the experimental and analytical results provided assurance that numerical simulations could be used to study the effects of different test parameters. The results of these studies will provide the basis for quantitative infrared thermography in which not only the presence but also the characteristics of a flaw can be established.

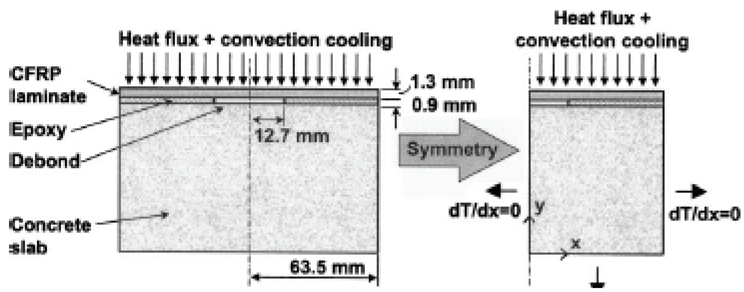


Figure 4-9. Test Object Used in Finite-element Simulations

4.4 Ultrasonic Method

F. Bastianini et al. (2001) (Italy) have applied ultrasonic non-destructive method with a new approach to assess bonding defects in composite strengthening structures. The proposed technique is similar to the usual pulsed echo ultrasonic analyses, but bonding defects are located through the amplitude of reflection echo rather than its delay time. This new technique has been experimentally demonstrated to be relatively unaffected by variations in glue thickness, very common in FRP strengthening of concrete and masonry structures. The effectiveness of the proposed technique has been successfully tested with different composite materials (CFRP and GFRP), applied to different substrates materials. A theoretical model of the principle of operations has also been developed. Such a technique appears useful for both quality control of the application and in situ surveying. Pulsed echo ultrasonic techniques are widely used in many engineering areas, which basically consists of sending a collimated ultrasonic beam inside the material under test, and then recording the echoes reflected by the discontinuity that the beam meets along its path (C-scan). Through the evaluation of the echo delay, the depth of the discontinuity is easily identified, as sound speed in the medium is constant and known. The ultrasonic behavior of FRP materials is similar to that of the homogeneous media, since the dimension of the typical discontinuity (i.e., the fiber diameter) is much smaller than the wavelength of ultrasonic vibrations commonly used. This remains true as long as the acoustic waves propagate in a direction orthogonal to the fiber axis, a condition easily verified in typical applications where fibers lie in the strengthening plane. In the direction of the fiber axis, ultrasonic properties are usually different due to the orthography of the composite and to waveguide effect of thin fibers. The homogeneous-like behavior allows traditional time-based ultrasonic echo techniques to be applied to FRP material.

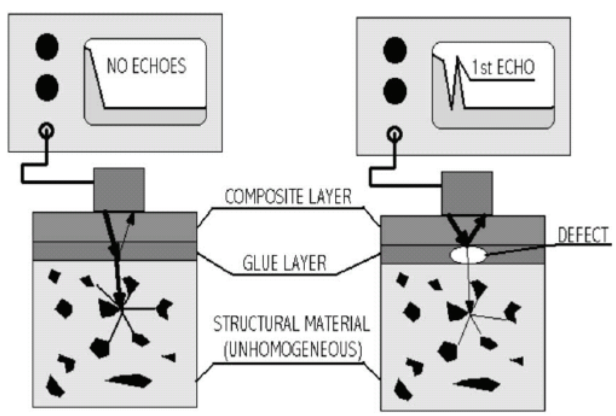
However, in the case of external FRP strengthening applied to roughly inhomogeneous materials, such as concrete and brick masonry, the time based technique is no longer effective. This is due to the high scattering attenuation of the inhomogeneous medium, which behaves almost like a perfect absorber, and generates a great number of short-spaced echo peaks that make the defect echo not easily distinguishable. The only way to avoid scattering is to use waves longer than the discontinuity dimensions, but this heavily degrades resolving power and makes bonding defects undetectable.

The technique developed is based on the relative amplitude of the only first echo peak, that is, the one that arises at the interface between the FRP and the underlying material.

At the interface between two different media, part of the energy of the incident vibration is refracted in the new one, while the other part is reflected back. The ratio between the energy of the refracted waves and the reflected waves is conditioned by the acoustical impedance mismatch between the two different media.

When a perfect bond between FRP and concrete exists, the acoustical impedance mismatch is small, as both FRP and the underlying material are dense solids and their sound speed is of the same order of magnitude, so the energy of the vibration is almost entirely transmitted to the concrete, where it is quickly absorbed by scattering. In these conditions, no echoes of notable amplitude will be displayed by the scanner at the FRP/concrete interface (see figure 4-10a).

When a bonding defect is present, the adherence between FRP and concrete is compromised by the presence of a thin air gap; in these conditions, the acoustical impedance mismatch is much bigger, as the density of the gaseous medium is very different from that of the FRP and its sound speed is about 10 times smaller, so a great amount of energy is reflected back to the transducer and a notable echo peak is displayed by the scanner (see figure 4-10b).



(a) No Defects Exist (b) A Bonding Defect Exists

Figure 4-10. High Frequency Ultrasonic Tests on External Composites Strengthening Applied to Concrete

Several experimental tests have been performed on a cylindrical concrete specimen wrapped with three layers of CFRP. Before the strengthening wrapping, four simulated bonding defects were introduced on the concrete surface, using a porous packing material. They were previously covered with PVC tape in order to avoid the thermosetting resin penetration into the pores. On the surfaces not subjected to the strengthening, some markers have been placed in order to recognize the position of the simulated defects. After the application of CFRP strengthening, the composite free surface has been scanned using a pulsed echo analyzer and the first echo amplitude has been recorded in every scanned position.
Figure 4-11 shows the setup and execution of the tests on the concrete cylinder.

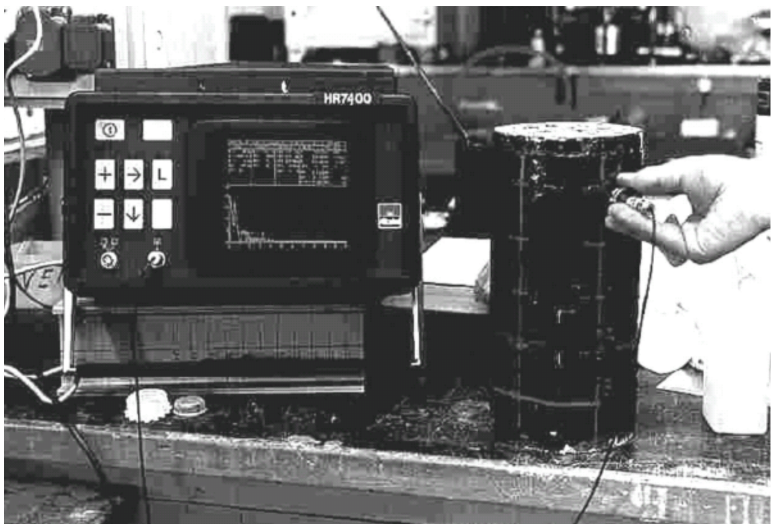


Figure 4-11. Experimental Setup for Ultrasonic Testing of Concrete Cylinder Wrapped with CFRP

Figure 4-12 shows a map of the composite surface where the gray scale is representative of the echo amplitude, starting from minimum value (white), up to the maximum (black): the four simulated defects are clearly located by the high-amplitude echo areas that have been marked. Similar results have been obtained employing different frequencies up to some megahertz, always using a coupling gel to minimize acoustical impedance mismatch between the transducer and the CFRP.

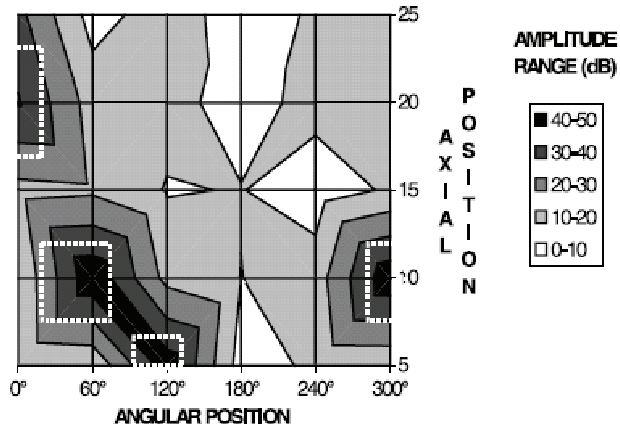


Figure 4-12. Amplitude Map of the First Echo on a Concrete Cylindrical Specimen Wrapped with CFRP. The High-Echo-Amplitude Areas (Dark Spots) Locate the Artificial Bonding Defects (Dashed Line)

4.5 Impact-Echo Method

Missouri Department of Transportation (MoDOT) and the Center for Infrastructure Engineering Studies (CIES) at the University of Missouri-Rolla have carried out massive investigations in a bridge located in Dallas County, Missouri, to provide installation criteria for FRP strengthening of civil structures (Ekenel and Myers, 2004: Maerz et al., 2004). This investigation covers measurement of surface preparations, evaluation of bond properties by pullout tests, detection of fiber alignment, and detection of delaminations formed between concrete substrate and carbon fiber reinforced polymer (CFRP) by non-destructive testing equipments. Several non-destructive testing systems were performed such as impulse-echo, ultrasonic, and microwave to detect and image the delaminations.

Because the CFRP strengthening works as an additional flexural or shear reinforcement, the reliability for this material application depends on how well they are bonded and can transfer stress from the concrete component to CFRP laminate. Ideally, designers prefer a CFRP laminate that is perfectly bonded to substrate concrete. The bond strength between an FRP sheet and concrete influences the structural behavior of concrete elements strengthened with FRP sheet bonding. The American Concrete Institute (ACI) Committee 440.2R document requires bond strength of minimum 1.4 MPa and failure mode of the concrete substrate (ACI, 2002).

The surface roughness also has a significant influence on bond strength. Therefore, it is necessary to determine an evaluation method for concrete surface roughness and to describe the relationship between bond strength and various surface roughness indexes. The most common method used to prepare the surface is sand blasting. The surface roughness of concrete can be varied by changing the application methods, such as adjusting the amount of sand discharged from the nozzle or the distance between surface and nozzle.

Another type of structural deficiency is air voids or delaminations between CFRP laminate and concrete substrate. Any of these surface defects may affect and significantly weaken the structural integrity and performance of the system; moreover, they may limit the life expectancy of the structure. Delamination can be caused by several factors, such as the presence of moisture in the concrete, significant changes in temperature during curing, and improper application. An undetected delamination may also cause fracture of the material. The American Concrete Institute (ACI) Committee 440.2R document requires the evaluation of delaminations and air voids between multiple plies or between the FRP system and the concrete with a minimum detectable size of 1300 mm^2. Some other criteria from ACI Committee 440 is: total delamination area should be less than 5% of the total laminate area and no more than 10 delaminations per 1 m^2, large delaminations (greater than 16,000 mm^2) should be repaired by cutting away and applying an sheet patch, and delaminations smaller than 16,000 mm^2 may be repaired by resin injection or ply replacement. He also reported an insignificant growth in delamination sizes after fatigue testing for 2-million cycles without environmental conditioning. Fiber alignment is an important issue that should be investigated during and after FRP placement because the performance of unidirectional FRP laminates is highly dependent on fiber orientation with respect to applied load direction. Depending on the severity of the misalignment, the difference between actual strength and stiffness of the FRP from assumed nominal values may become critically high and may cause of rejection of the system. ACI 440.2R-02 reports that fiber misalignment of more than 5 degrees as compared to design drawings should be evaluated for acceptance.

One of the main concerns about bridge rehabilitation is early determination of the above mentioned problems to ensure safety and to assist in management of the bridge system. Since the quality of the FRP products is very consistent and satisfactory due to the manufacturer’s quality assurance system, the main remaining issue is quality of work performed during rehabilitation or strengthening. The conventional methods involve visual inspection or destructive testing; however, it is obvious that visual inspection cannot provide quantitative and objective information and destructive testing may have adverse effects on the integrity of bridges. An example of this conventional testing is the coil tap test of delaminations. This method involves basically using a small hammer or a steel bar to tap the FRP bonded surface (after curing) to detect air voids, because a perfectly bonded FRP generates a different audible noise from one that is not perfect. However, even though this method is low technology and simple, it is more subjective and less reliable because it needs an employee with a discerning ear. Hence, efficient, reliable, cost-effective, portable, hand-held nondestructive testing (NDT) devices, which do not compromise the structural integrity during the inspection of rehabilitation work, are in demand. Moreover, this device must be user-friendly and the outcomes of these devices must be easy to interpret. Several NDT methods are currently available such as impact-echo, microwave, thermography, and ultrasonic; however, they should be validated before use and all factors affecting their reliability should be identified. Currently, there are no standard NDT procedures that control the quality and assess the integrity of bonded FRP composite systems used in civil engineering applications. One of the purposes of the work described in the paper was to create an environment and system to test the NDT methods in delamination inspection of CFRP utilized bridge rehabilitations, such as impact-echo, microwave, and ultrasonic.

One of the purposes of this investigation was to develop reliable and capable methods to detect voids and delaminations of a specified maximum size in FRP repair systems. The results of this investigation will help obtain a better understanding of the permissible size of individual detectable delaminations, their location in the structure, and delamination area over a given structure. Severe environmental conditioning effects, coupled with fatigue loading, will also be addressed.

For this investigation, 15 CFRP laminates with dimensions of 20”x24” were installed on various spots of abutment and bents. Six CFRP laminates were installed on the south abutment. Four of the CFRP laminates were placed on the south side and one on the east side of the south bent. These laminates were installed on roughened surfaces. Two other CFRP sheets were placed on the north side of the same bent. These sheets were installed on unroughened surfaces and served as control samples. Finally, two CFRP sheets were placed on the corners of the lower part of north bent columns, as shown in figure 4-13. These sheets were placed close to the water level in order to study the wet-soak and freeze-thaw effect for next five years.

Figure 4-13. CFRP Laminates with Delaminations on South Abutment and North Bent

Delaminations were created on all CFRP laminates. Delaminations were formed by applying pressured air beneath the CFRP sheet when the epoxy was in a fresh state. Because it was hard to control pressured air, the number and the sizes of the delaminations could not be controlled. The final shapes were formed by rolling a roller spike around the delaminations. Each single CFRP sheet contained different sizes and numbers of delaminations. Figure 4-14 shows how the delaminations were formed.

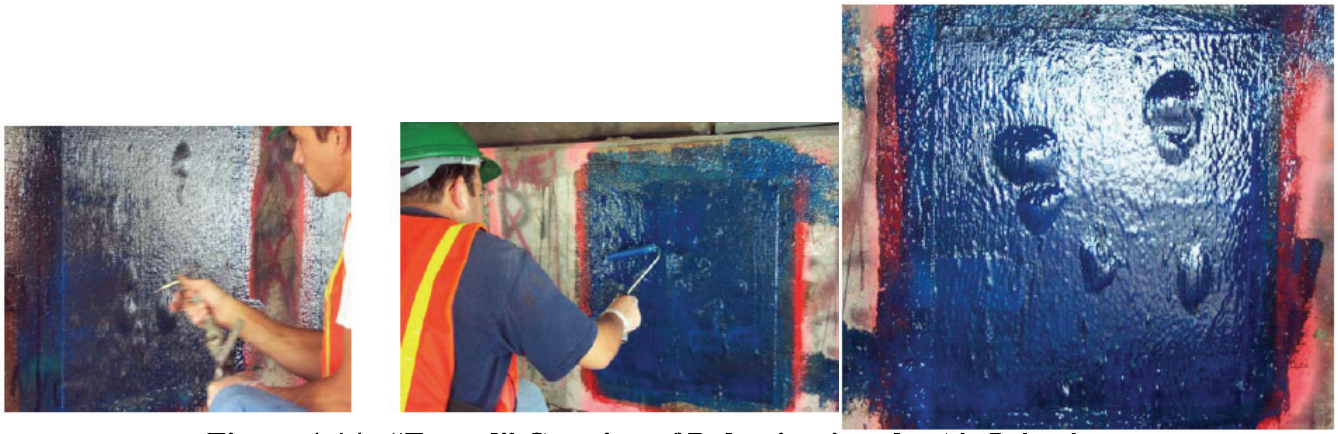


Figure 4-14. "Forced" Creation of Delaminations by Air Injection

Delamination of the FRP materials after installation resulted in decreased stiffness and decreased load bearing ability. A delamination with a surface area of 1 square inch is believed to be the threshold for which repair should be considered. To measure delaminations, an Olson Instruments impact echo tester (figure 4-15) was specially modified with an air coupled receiver (figure 4-16), and frequency domain analysis was employed to uniquely identify delaminated areas.

Figure 4-15. Olson Instruments Impact-Echo Tester

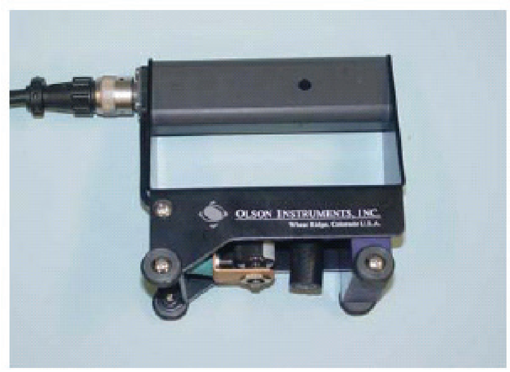


Figure 4-16. Impact-Echo Tester Modified with Air Coupled Receiver

The impact echo delamination measurements were successful in identifying the "forced" delaminations. In addition, some small unplanned delaminations were found. Delamination measurements are somewhat time consuming, taking about 30 minutes to measure a 2.75 square foot section at 1" centers. In addition, the sampling points have to be marked before measurements can take place.

4.6 Acoustic Guided Waves Method

Through a Small Business Innovative Research (SBIR) Project titled "Field Portable Infrastructure Fiber-Reinforced Polymer Composite Inspection & Evaluation System using Ultrasound Technologies" with the US Army Corps of Engineers, Engineering Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL), Physical Acoustics Corporation (PAC) developed an NDE technique for inspecting FRP retrofitted concrete and masonry structures. The technical aspects of the technique were studied during Phase I and Phase I Option of the project (Godínez-Azcuaga et al., 2004; Trovillion et al., 2004; Ekenel et al., 2005). During Phase II, PAC designed and constructed a field-portable inspection system for the nondestructive inspection of FRP retrofitted concrete structures. At the completion of Phase II in January 2004, the FRP-Concrete Inspection System (FRPCIS) was delivered to ERDC-CERL.

The FRPCIS was developed on a hand-held computer platform and uses a newly developed probe equipped with acoustic rolling sensors and mechanical encoders for position tracking. FRPCIS is capable of displaying RF waveforms and processing the data to produce C-scan images of the inspected structures. FRPCIS is used for inspecting seismic retrofits in Army facilities; however, the system could be used on other Army applications of thin layered FRP composites. These include the composite skins in planes and helicopters, blast protection fabric systems, rotorcraft blades, and ballistic protective inserts (BPI) in personnel armor.

The AU technology consists of sending low frequency acoustic pulses at a predetermined angle of incidence into a material under inspection. These acoustic pulses travel through the material and are reflected by the different interfaces inside the sample. If a discontinuity (delamination, debond, etc.) is present inside the material, the reflected acoustic energy changes, revealing the presence of the discontinuity.

In order to determine the optimal inspection parameters for a particular composite structure (incidence angle, frequency, and pulse length), a wave propagation model for multi-layered structures is used. This model is based on a plane wave propagation model using the Thomson-Haskell transfer matrix for multilayered media. The characteristics of the composite material such as layout and material properties are used as input data to the model. This model provides the flexibility necessary for the system to be used in the inspection of different composite systems. For instance, if a composite with glass or aramid fibers is used, the material properties of these composites would have to be input into the model and the optimal frequency and angle of incidence to inspect those composites will be calculated by the model.

The system used in the inspection does not have the ability to modify the incidence angle so the inspection was performed at normal incidence. The characteristics of the system are:

- Small and portable, with maximum dimensions of 150mm x 150mm x 50mm.
- Battery operated (maximum continuous operation of 8 hrs with rechargeable battery package).
- Capability to detect defects 6mm in diameter.
- PCMCIA interface for data logging storage.

- Capability of generating A- and C-scans.
- Flash memory for data transfer.

The system consists of several components: a CPU platform, an AU board, a unique Rolling Sensor Probe (RSP), and control software that allows the different components to communicate and to generate C-scan images. Figures 4-17 through 4-22 show the FRP-Concrete Inspection System (FRP CIS).

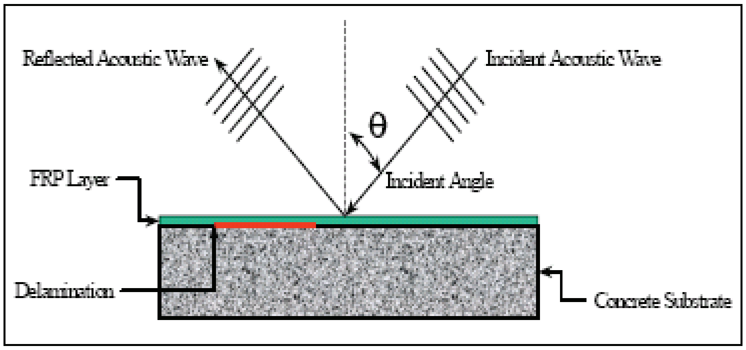


Figure 4-17. Setup Used for the Theoretical Simulation of Wave Propagation on FRP-Concrete Structures

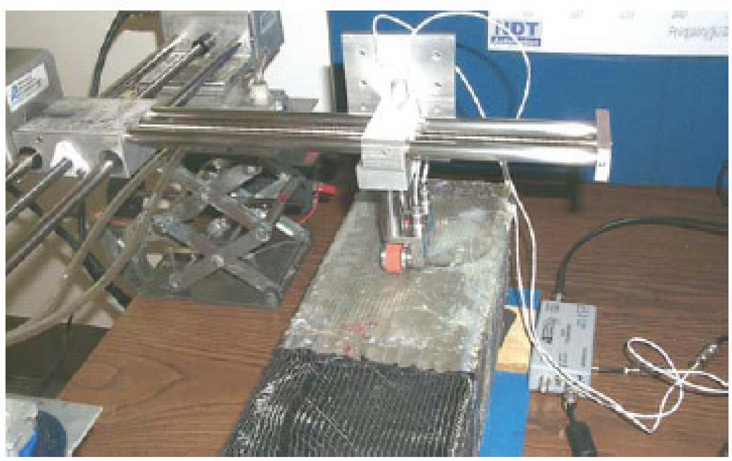


Figure 4-18. Inspection of a FRP-Concrete Sample Using Rolling Sensors Mounted on a Scanning Bridge

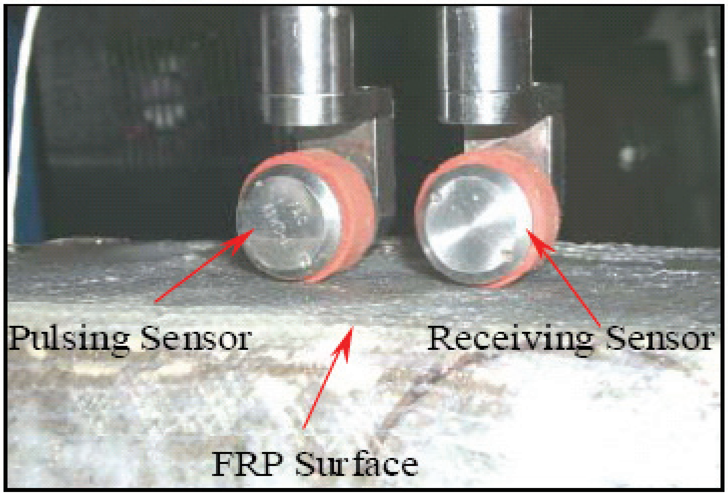
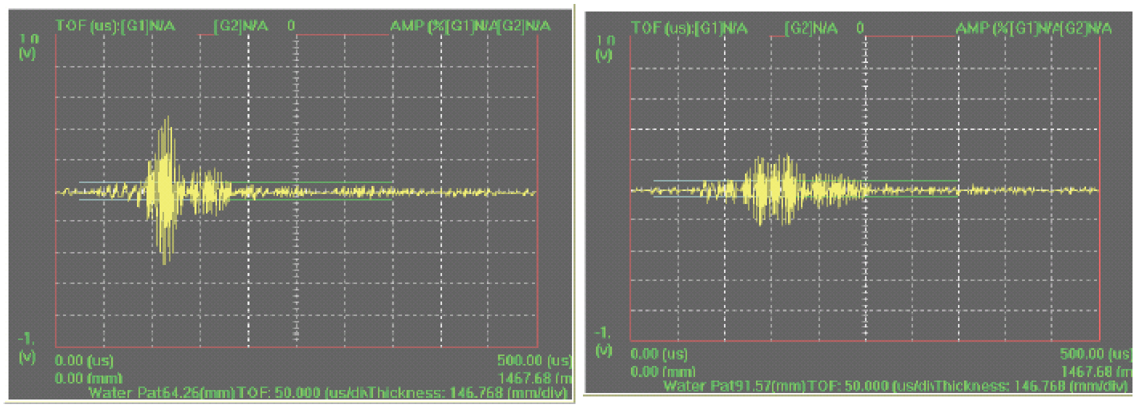


Figure 4-19. Detail of the Rolling Sensors During Inspection of an FRP/Concrete Sample

Figure 4-20. Inspection System for Composite Wrap Inspection on Concrete Structures



(a) (b)

Figure 4-21. RF Signals Recorded with Rolling Sensors on an FRP/Concrete Sample. (a) Bonded Area, (b) Debonded Area

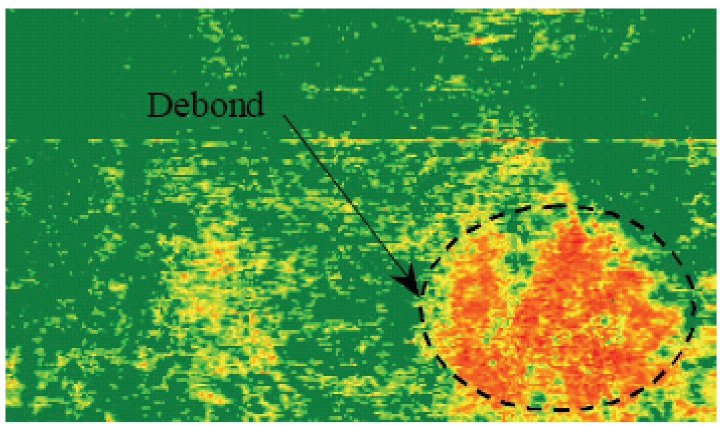


Figure 4-22. C-Scan Image of an FRP/Concrete Sample showing a Debond between the FRP and Concrete

CHAPTER 5
EVALUATION OF NDT/NDE TECHNOLOGIES FOR FRP-JACKETED HIGHWAY BRIDGE COLUMNS

5.1 Vibration Method

Advantages:

- Ability to locate damage.
- Able to rate the deterioration condition in a global manner for entire bridge due to the global characteristics of structural modal parameters.
- Effectively used for long term and on-line damage detection and health monitoring.

Disadvantages:

- Requires precise and reliable baseline data, which may be difficult to retrieve for a bridge in service for years.
- Need intensive and complicated computation for analytical and experimental modeling.
- Sensitive to environmental effects such as thermal expansion or debris collecting at expansion.
- Indicator sensitivity to damage relies on the damage location.
- Not sensitive to incipient-type damages.

5.2 Microwave (Electromagnetic) Based Method

Advantages:

- Provides critical information concerning anything that lies below the surface of FRP such as debonding.
- Fast, reliable and safe.
- Provides a 2D or 3D image of the scanned areas.

Disadvantages:

- Microwave method cannot penetrate conductors such as metals.
- Very sensitive to site specification due to the limited depth of penetration of radar in conductive environments, such as in salt water and water-saturated clay.

5.3 Impact Echo Method

Advantages:

- Testing system is small and less costly.

- Requires access to only one side of the structure.
- Determines depth and width of cracks.
- Has been effectively applied to many different types of concrete structures, including plate-like structures, such as bridge decks, slabs, walls, beams, columns, layered structures, and hollow cylindrical structures.

Disadvantages:

- Difficult to detect smaller cracks and discontinuities due to the relatively low frequencies involved.
- Structural geometrical effects (multiple ducts, crossing reinforcements) largely affect correct data interpretation.

5.4 Thermography Method

Advantages:

- Area-testing technique that can form 2D image to survey a larger area for problems (others are point or line testing).
- Remote-sensing infrared thermo-graphic data collection technology results in major saving in time, labor, equipment, traffic control, and schedule.
- Equipment is safe and not very expensive.

Disadvantages:

- Depth or thickness of a void cannot be determined.

5.5 Ultrasonic Method

Advantages:

- Imperfections can be detected in metallic and nonmetallic materials.
- Defect can be detected and located effectively even in very thick materials.
- Only single-surface accessibility is required.
- Both internal and surface discontinuities may be detected.
- 3D discontinuity imaging is possible.
- Rapid testing capabilities.
- Many portable instrumentations for field testing have been commercially available for decades.
- Inspection costs are relatively low.

Disadvantages:

- Difficulties in coupling energy to rough surface.
- Impractical to inspect complex shapes and very tight cracks.

- Interpretation of the signals received and defect imaging are complex.
- Special and more expensive scanning systems may be required for inspecting large surfaces.

5.6 Combined Methods

In some circumstances, the reliability and usefulness of data derived from NDT/NDE can be improved by using a combination of tests. In most cases, visual inspection can be adapted to represent a first step and preliminary investigation, while the second and third may be used to check the veracity of the data to provide additional details. A typical suggested procedure is as follows:

- Visually examine the appearance of a jacketed column to observe if there is any cracking in the FRP layer and the concrete.
- Visually examine FRP layer debonding and bulging that would be spatially large and relatively severe in nature.
- Apply the infra-thermography method to obtain full-field picture.
- Implement the impact echo scanner to assess the details.

CHAPTER 6
CONCLUSIONS, RECOMMENDATIONS AND FUTURE RESEARCH

The vibration, microwave-based, thermography and ultrasonic methods all show promise for use in NDE/NDT applications. To date, however, there is no single NDE/NDT technology that can be applied in the field to detect all kinds of damage at different stages of the columns of highway bridges. Further study on hardware/software options and in situ applications should be conducted.

To date, papers and reports where the authors declare that one NDE method can be applied to all types of damage inside the FRP-jacketed bridge columns have not been located. In all surveyed methods, impact-echo scanning appears to be the most promising method, since it is economical, safe and has feasible characteristics.

Combined NDE, such as using microwave-based technology to detect location damage and using mechanical-based technology to detect the overall strength reduction, may have a more promising future. However, there are no systematic reports on these topics so more research must be conducted to ensure their applicability.

The following issues warrant further study:

1. Damage model of bridge columns

The way a column, both newly built and retrofitted, is damaged under earthquakes and how it is damaged should be modeled mathematically as accurately as possible. Such modeling can help define a clear direction for using and evaluating the technologies for damage detection in columns. Without this overall picture, current development of damage measurements will still only be approximations. This is because the damage detection, as well as further predictions of remaining life and capacities, cannot be established solely on experience. Theoretical approaches must be developed. Such a damage model should include:

- ***Type of damage:*** In the above text, the type of damage is described qualitatively. For an accurate damage model, quantitative descriptions of damage must also be obtained.

- ***Cause of damage:*** Further descriptions to explain the causes of the above-mentioned damage is needed. Various extra-large forces including moments as well as their combinations can be used as damage indicators. Large deformations/displacements, including rotation angles, can also be used as indicators, as well as local and global energies, etc. Other parameters such as aging, fatigue, chemical and environmental, should also be considered.

- ***Growth of damage:*** Initially formed damage and the growth or development of the damage must be modeled, which includes the causes of the growth rate and the cross effect of various types of damage.

2. Relating measured parameters with the damage model

Once the damage model(s) is established, the measurement parameters, such as modal and vibration parameters, micro-wave reflections, thermo-images, sound reflections, etc. need to be related to the damage model as well as damage growth.

The authors of this report believe that this study, which may be very labor intensive, is an important step to making the experiments in laboratories applicable to real-world applications.

Statistical studies, theoretical and numerical simulations will be involved to interpret the measured parameters. Test repeatability will be an important issue in this phase of future investigations.

3. Methods to increase the measurement signal-to-noise-ratio

To date, one of the common problems in all the aforementioned technologies is the low measurement signal-to-noise-ratio. In many cases, the signal-to-noise-ratio is less than one, which makes the damage measurement unreliable.

The measurement signal-to-noise-ratio must be precisely defined. Indicators to judge this ratio are also needed, as are methodologies and techniques to improve the measurement.

4. Better algorithms for system identifications

To date, many algorithms are available, and based on methods including image analysis and pattern recognition, system identification and inverse problems, correlation and spectrum analysis, wavelet theory, Kalman filter and Wiener-Kolmogorov filter, nonlinear input-output identifications, finite-element method and other numerical methods such as fussy-logic model, Nero-network model, etc. These need to be evaluated further to determine the better or best methods.

5. Reliable sensory systems for field-testing and health monitoring

This requirement is always needed. Better transducers, such as smart sensors, high resolution-high dynamic range sensors, wireless sensors, data compression techniques, etc. should be considered.

6. Effective network for signal transfer and data storage and management

An effective data transmission network, from the original signal measurement to the final decision making for determining whether to repair or replace a column, needs to be studied in greater detail. This research involves not only technical development, but also social and political considerations. Codes that help bridge engineers to make decisions about column inspection, retrofit and replacement based on the NDE technologies should be developed.

7. Remaining life prediction

After a strong earthquake, if the damage and its extent in a bridge column jacketed by FRP are measured, the bridge owner faces the most important question: how many traffic loads can safely be applied to the bridge? And, how long is the remaining life of the column?

Computational Inference - Earthquake damage to bridge columns results, in some cases, from low cycle fatigue effects. Therefore, a companion assessment strategy based on a computational methodology to predict the remaining life of earthquake-damaged jacketed columns should be developed. This approach would use ground motion records to assess previous earthquake-induced inelastic displacement history and, hence, damage to pier columns. On this basis, the remaining life of the columns can be inferred.

8. Consideration of multiple hazards

To date, most research on NDT/NDE of bridge columns is based on single or a very limited number of causes of damage. In real-world applications, the bridge column may be subjected to multiple hazards. Therefore, the retrofitted columns subjected to multiple loading at normal and severe scenarios need both theoretical and experimental study.

9. Combined methods

Due to the lack of successful signal technology that is able to solve the problem of using NDT/NDE to detect column damage, it is suggested that combined techniques be used. Although in this report several combined methods were investigated, it was found that it is far from sufficient to systematically combine targeted measurements.

For example, one measurement may be used to detect local damage and another to detect global problems. Or, one measurement may be used to detect damage on the surface and another may be used to find deeper problems. One measurement may be used to detect damage associated with certain materials and another may find damage in other materials.

In fact, the NDT/NDE for retrofit columns is indeed a system engineering problem. The authors believe that only the integration of several technologies can provide both comprehensive and accurate results.

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