QUALITY AND MONITORING OF STRUCTURAL REHABILITATION MEASURES

Part 2: Review and Assessment of Non-destructive Testing (NDT) Techniques

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1 INTRODUCTION

1.1 RATIONALE OF INVESTIGATION

In the previous part of this report series [1], the reader has been provided with the description of a vast array of possible material defects or anomalies, which can be introduced to fiber reinforced polymer (FRP) composite laminates in the course of structural rehabilitation efforts. Given the four predominant stages of rehabilitation, including the intrinsic materials, site preparation, field installation and service, defects were categorized in accordance to their initiating stage and factors contributing to such defects as well as the most probable effect on overall integrity of the FRP-concrete system were discussed. While the preceding discussion served as an essential step towards developing an overall understanding for the *effect of defects* on externally strengthened concrete structures, it solely provided the reader with information on eventual material flaws and installation deficiencies.

In addition, field inspectors must be familiar with possible non-intrusive techniques that allow the in-situ detection of such defects. Here, techniques sought are those that can be applied to the structure subsequent to conclusion of the rehabilitation work, i.e. in service, and should not be confused with quality control techniques outlined in the previous report, such as viscosity tests, DSC, DMTA or FTIC inspections. While a number of defects discussed in the previous part can be identified and possibly characterized through visual inspection, the majority only occurs inside the composite material, at the concrete/composite interface or within the concrete substrate. Generally, these discontinuities can neither be identified nor characterized through simple inspection methods once the composite overlay has been installed and reached its cured state. Instead, their detection often demands utilization of more sophisticated testing equipment- and procedures as well as an experienced operator/inspector with extensive experience in composite inspection and interpretation of data extracted from such equipment.

As part of this report series, the present discussion will provide a state-of-the art review of potential non-destructive testing (NDT) techniques for defect detection in carbon-fiber reinforced polymer (CFRP) materials through review of past and current projects, including industrial applications, research projects, as well as methods under current industrial development. Both, theoretical and practical aspects of each individual technique will be addressed, including information on equipment, portability, data storage as well as their capabilities and limitations. Subsequently, these findings will serve to assess the suitability of each individual method towards in-situ inspection of CFRP-rehabilitated concrete components.

From the authors' perception, an ideal inspection system, if such exists, shall meet a variety of criteria, including the following:

- NDT systems shall provide the capability of detecting a wide range of material discontinuities without negatively affecting the rehabilitated structure in performance, serviceability or appearance
- Inspection must be performable in real-time and over reasonably large areas (full-field) without sacrificing the ability of localized inspections (near-field). Former

requirement may necessitate utilization of more than a single NDT system, as most full-field techniques lack sensitivity to localized defects.

- All equipment must be portable, easy to handle and operable in a variety of positions/arrangements to allow for inspection of overhead and tight regions
- Data acquired from an NDT-system shall be representative of the actual defect parameters (type, size, shape, location) at all times with little or no susceptibility to changes in environmental conditions, unless they are well understood and can be accounted for in subsequent data interpretation

The indisputable benefit of non-destructive testing lies in its capability to detect and, within limits, characterize a range of subsurface material discontinuities, including voids, delamination, fiber breakage or moisture accumulation in existing structures or components thereof, which otherwise restrict insight on their current material state. Through non-destructive inspection, engineers can obtain valuable information on eventual changes in the state of a material, including the onset of fatigue cracking or growth of formerly microscopic defects towards a critical level. If operated by qualified personnel, real-time inspection and data interpretation can allow instant assessment of a structure's integrity and serviceability. Hence, once deficient regions are identified in the field, immediate action can be taken to initiate the required repair procedures as to retain serviceability and safety of the structure. Also, feasible NDT methods should be capable of detecting both global and local flaws to permit rapid scanning of larger areas, while allowing for detailed distinction between good and defective areas on a local level.

CFRP-rehabilitated structures, in particular, do not benefit from extensive research in regards to short- or long-term deterioration as often induced by harsh and fluctuating environmental conditions. Hence, the civil sector is currently seeking methods to monitor rehabilitated structures non-destructively to allow in-depth investigation towards finding the types of discontinuities that are most frequently encountered as well as their growth and effect on structural performance with time. Recently, a variety of methods have been studied extensively for use on laminated composite materials [2], [3], [4], [5]. However, applicability of most NDT methodologies to CFRP-rehabilitated concrete structures remains largely uncertain. Unlike the material composition found in most composite aircraft structures, rehabilitated infrastructure components are comprised of a concrete substrate material, a typically non-uniform interfacial region of primer and/or comparable resin paste as well as an anisotropic fiber-reinforced composite laminate. It may be assumed that this constellation of materials limits the applicability of some well-established NDT methods for aerospace testing, while possibly favoring other techniques that have not yet been focused on extensively. It is the objective of this discussion to shed light on NDT methods that are potential candidates for inspection of CFRP-rehabilitated infrastructure, with special consideration of the unique material composition, desired sensitivity on a structural level, as well as several practical aspects desirable for in-situ application.

1.2 Non-destructive Testing of Composites

For centuries, relevant material properties like ultimate strength, yield point or impact resistance have been determined through a number of destructive test methods in order to provide comprehensive information on material behavior. Unarguably, the advantage of a destructive test is given by the fact that materials can be exposed to a variety of load conditions without the necessity to remain functional upon completion of a test. While this methodology has long served in optimal design of structures, it can rarely be applied to evaluation of civil structures.

Today, the continuously rising demand on civil- and transportation infrastructure has led to the need for finding alternative testing techniques, which allow the inspection of existing structures (airplane wings, bridge decks, etc.) without damaging or dismantling individual components. The impetus for such action is largely based on the need to ensure continuous safety and provide means of monitoring their overall 'health'. While much information on a structures' physical condition can be extracted from visual inspections, most internal damage, namely cracking, corrosion, presence or formation of voids as well as moisture accumulation can rarely be identified per se and thus demand more sophisticated methodologies.

In theory, non-destructive testing shall provide information on material properties while neither influencing the material in its current state, nor requiring disassembly or any form of modifications that would cause extensive service disruptions possibly restricting serviceability over extended periods of time. While the term 'destructive' can be of broad context, its onset should be defined as the instant a component undergoes initial forms of permanent, non-reversible modification. These include changes in chemical or molecular structure as well as stages at which it experiences severe degradation and can no longer serve the original purpose it has been designed for. This implies that a component, which is tested non-destructively, shall retain its original strength, stiffness, chemical consistency, and appearance throughout the entire procedure as well as for a substantial period thereafter. Although literature offers a seemingly endless array of definitions for non-destructive testing, the following was found to provide a suitable foundation for the subsequent discussion:

> *A process that does not result in any damage or change to the material or part under examination and through which the presence of conditions or discontinuities can be detected [6].*

Similar to the multitude of definitions for non-destructive inspection, several abbreviations are commonly used by field inspectors and the non-destructive testing industry. These include non-destructive testing (NDT), non-destructive evaluation (NDE), and non-destructive inspection (NDI). While this terminology is often used interchangeably, distinct differences exist. As may be noted from Figure 1-1, both NDT and NDI refer to the inspection process itself, i.e. testing of a part in a non-destructive fashion, leading to identification of defects/discontinuities with possible findings on defect type, location, size and shape. However, NDT and NDI do generally not assess the severity of damage on either a local or global scale. Instead, the effect of damage on system behavior is mostly accomplished through a subsequent evaluation process, implicated by the term NDE. Here, data collected through testing/inspection is evaluated and interpreted to assess its impact on integrity and performance of the inspected object. Consequently, apart from a systematic methodology for localization and dimensioning of eventual material discontinuities, non-destructive evaluation necessitates an understanding of significance and structural impact of found defects. As presence of material discontinuities, introduced during erection, rehabilitation or service of a structure does not imply a reduction of its performance or safety, NDE represents the most challenging task.

In this context, test methods developed to date can be classified into four levels, according to the specificity of the information provided by the individual technique [7], as depicted in Table 1.

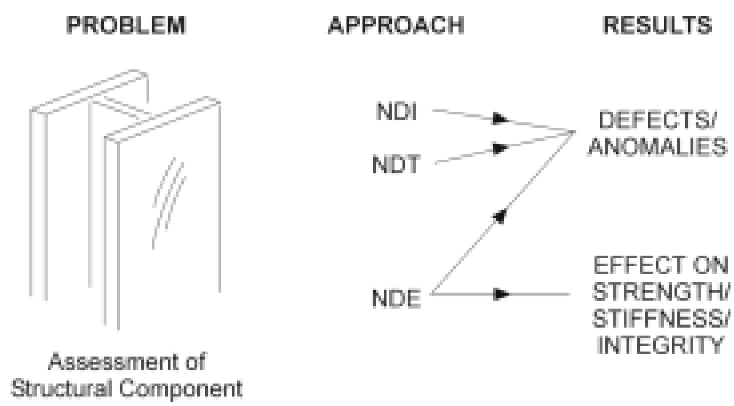


Figure 1-1: Differentiation between common non-destructive terminology

Because the majority of methods discussed in the present report are primarily focused at localization and dimensioning of anomalies, they must be categorized as being either Level I or Level II, depending a variety of factors, including system sensitivity, member geometry, environmental conditions, etc.

To perform a non-destructive test, the object is typically exposed to a single form of external media (radiation, stress, temperature, etc.) emitted from the testing equipment, which must be capable of partially or completely penetrating the material. However, some forms of NDT techniques do not require penetration of the test object to reveal anomalies, such as optical methods. Others utilize sensors that are embedded inside the structure, and hence make use of yet an alternative testing methodology. Techniques that employ sources, which cannot be interpreted by human perception (ultrasound, x-ray, etc.) must employ a suitable detection media coupled to an output device such as a monitor/screen in order to display the recorded information, as schematically depicted in Figure 1-2. Finally, the recorded information can be displayed in a form that is detectable for the inspector. This is imperative, since incorrect interpretation of images can lead to erroneous conclusions about the composition of a material. Hence, apart from choice of method, success of NDT depends largely on experience and expertise of the inspector.

Table 1: Designation of NDT-Levels

DESIGNATION	PROVIDED INFORMATION
LEVEL I	Methods that only identify presence of anomalies
LEVEL II	Methods that identify presence as well as location of anomalies
LEVEL III	Methods that identify presence and location of anomalies and estimate their severity
LEVEL IV	Methods that identify presence, location, and severity as well as structural impact of anomalies

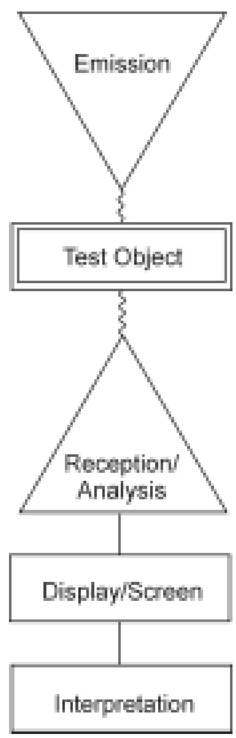


Figure 1-2: Schematic illustration of the NDT methodology

Given the fact that fiber reinforced polymer materials are comprised differently from traditional NDT materials, such as steel, a concise knowledge of the property differences of both materials with respect to non-destructive testing becomes indispensable. While most NDT-techniques have initially been used to locate cracking or other imperfections in metals, they have later proven to be suitable for detection of delamination, moisture or porosity in laminated composite materials. Nevertheless, prior to discussing the various NDT techniques towards their suitability for detecting intrinsic material discontinuities, one must be aware of differences between isotropic, ferromagnetic materials, such as steel, and anisotropic, amorphous materials, such as CFRP composites.

Possibly, the most important difference between metals and composite materials is the fact that former display a homogeneous structure, whereas composites contain two inherently different constituents, namely fibers and matrix. Consequently, composites are likely to experience different values for wave velocity, thermal conductivity or electromagnetic inductivity along various orientations within the material. Furthermore, they are not ferromagnetic, i.e. they cannot be permanently magnetized, which limits the use of techniques that are based on the principle of electromagnetic induction. Although carbon fibers are known to possess inductive properties, only certain electromagnetic techniques have proven to be feasible inspection tools. Finally, signal attenuation plays an important role in ultrasonic testing of composite materials, since it often results in a rapid reduction of signal strength. Due to a large number of fiber/matrix interfacial regions, ultrasound intensity in composite structures tends to decrease significantly with distance, making testing of thick parts (>1 inch) extremely difficult.

1.3 OVERVIEW OF TECHNIQUES

Many early discoveries, such as the piezoelectric effect in the 1880's along with x-rays in 1895 have formed the basis for most of today's NDT techniques. Over time, additional techniques were developed either independently or based on these general theories, with several modifications to better adapt to material-specific characteristics. Although most techniques may have initially been developed for use in other fields, such as the medical or military industry, they have later proven useful for NDT purposes. Continuous progress in this field, particularly through the use of modern computer software along with a constant growth in data storage capabilities, has lately allowed an even more successful utilization of these technologies. Particularly, application of fast-fourier transform (FFT) functions and computer-assisted tomography (CT) has allowed for more sophisticated presentation and evaluation of test results [8], [9]. Also, technological improvement has led to an overall increase in sensitivity of most methods.

The majority of current NDT techniques can be assigned to one of the following categories, including:

- Visual Testing (VT)
- Acoustic Impact Testing (AIT)
- Penetrant Testing (PT)
- Ultrasonics (UT)
- Radiographic Testing (RT)
- Thermographic Testing (TIR)
- Magnetic Particle Testing (MT)
- Eddy Current Testing (ET)
- Microwave Testing
- Optical Methods
- Acoustic Emission (AE)
- Ground-Penetrating Radar (GPR)

Moreover, a variety of so-called *data-collection techniques* exist that are not considered traditional NDT methods, including:

- Strain Measurement Techniques
- Modal Analysis
- Rapid Load Testing

Apart from the preceding list, a number of sub-techniques have been developed, which will be discussed in corresponding sections of this report.
Although most of the formerly listed techniques are applicable to CFRP, several methods have limitations due to the distinct material properties of composites. As mentioned earlier, methods utilizing the conductive nature of materials are most commonly applied to inspection of metals. Although carbon fibers are conductive, they are not ferromagnetic. Thus, methods like eddy current testing and microwave inspection are limited in their applicability, while testing via magnetic particles must be considered virtually impossible. Consequently, these techniques will not be discussed in further detail.

As outlined previously, methods can be distinguished based on the amount of area that can undergo simultaneous inspection. In this context, it should be noted that a number of above methods are solely used for localized inspection, including AIT, UT, ET, microwave testing and AE, while others, such as TIR, RT or optical methods may be applied for both near- and full-field assessments. In common practice, near-field processes serve the localized inspection, in either a randomized fashion or at specific locations where defects are known to exist from a preceding, global NDT inspection. In addition, NDT has been used to assess overall structural integrity, in that data is collected from discrete sensors situated throughout an entire structure. Hence, NDT and data collection methods can be assigned to the former acquisition fields, namely, near-field, full field, and global, as schematically depicted in Figure 1-3.

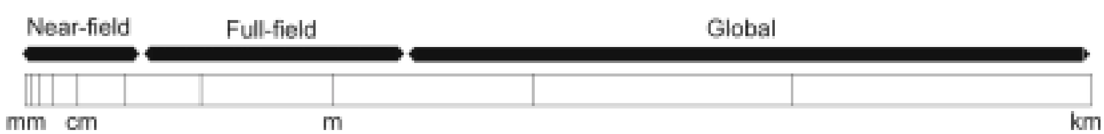


Figure 1-3: Field-of-acquisition for various inspection techniques

As may be expected, testing performed in a near-field manner generally results in highest sensitivity, which generally decreases as the inspection setup is changed towards a more global arrangement. This effect is known to exist for techniques such as thermography or optical methods, both of which have been used successfully in near- and full-field arrangements [10], [11], [12], [13]. Hence, an increased field of acquisition, as enabled through full-field or global inspection typically comes at the expense of sensitivity, i.e. the minimum detectable defect size will tend to increase. As may be noted from Figure 1-3, this decrease in sensitivity is particularly pronounced in global testing, a methodology that, although in wide industrial and experimental use, lacks sensitivity to the degree desired for the current study. Nevertheless, due its frequent use and widespread acceptance, global testing methodologies will be included in subsequent chapters of this report.

1.3.1 The Electromagnetic Spectrum

Many naturally occurring phenomena are based on emission or interaction of electromagnetic radiation. On earth, electromagnetic radiation is present at all times in form of cosmic radiation, naturally occurring x-rays, heat radiation, visible light as well as various man-made sources, including radio- and radar equipment. Based on the premise that all electromagnetic radiation travels at the speed of light, commonly denoted as c, the various forms of radiation can be distinctly separated by their specific frequency, f. As such, they can also be considered in terms of their specific frequency range, which can be related to wavelength, λ_l, via the relationship

$$\lambda_l = \frac{c}{f} \tag{1}$$

Many forms of electromagnetic radiation build the foundation for non-destructive testing. Hence, thorough knowledge of the characteristic properties of each type of electromagnetic radiation is indispensable for much of the subsequent discussion. Figure 1-4 illustrates the most common forms of electromagnetic radiation utilized for NDE purposes and their corresponding wave parameters.

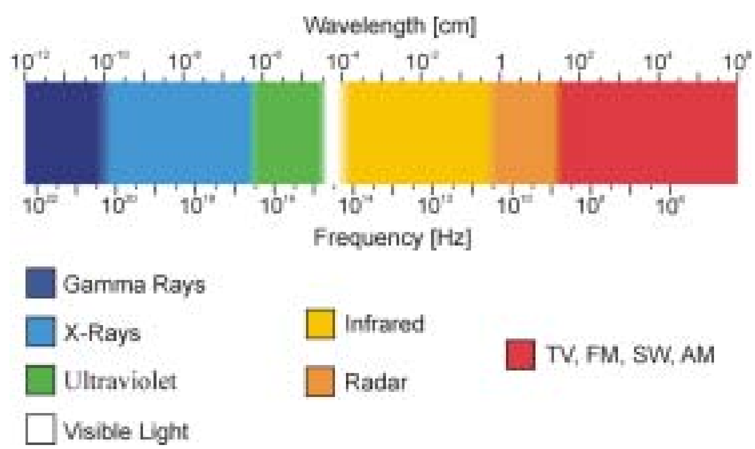


Figure 1-4: The electromagnetic spectrum

1.4 NDT Applications

Contrary to controlled laboratory conditions, in-situ inspection of materials or structures can pose significantly different demands on an NDT system. In a given environment, a variety of external influences that may complicate the inspection process can oftentimes not be controlled. For instance, large temperature fluctuations tend to alter the efficiency of thermographic imaging or ultrasonic inspection, since most materials undergo slight changes in properties, including wave propagation speed or emissivity [6]. Furthermore, the typically smooth surface texture found on laboratory specimens can differentiate tremendously from conditions found in the field. As might be expected, NDT techniques are of limited use for structural health monitoring if they are suitable only for laboratory environments. Consequently, a potentially successful inspection method must encompass an array of user-modifications in order to adapt to the naturally changing conditions in a field environment.

One of the most important in-situ inspection techniques, if not the most important, is visual inspection. Although one might not be readily aware of the fact that visual inspection is performed at almost any instant during preparation, installation and service monitoring it provides the basis for all other inspection methods. Without adequate vision and proper judgment of visual perception, none of the previous NDT methods will be useful for defect detection. In many cases, defects like moisture accumulation, delamination, excessive fiber waviness or sagging may easily be identified visually and do not necessitate use of more sophisticated techniques. However, human perception is often insufficient for locating defects that are predominantly found in subsurface locations. Hence, inspection often necessitates additional equipment that is capable of closing the gap between human perception and modern technology. Nevertheless, the importance of visual inspection cannot be overemphasized and remains one of the most powerful NDT tools. For all inspection, visual examination should be the primary initiative before conducting automated measurements.

To date, a limited number of in-situ non-destructive testing has been conducted on CFRP-rehabilitated concrete structures. In contrast, extensive testing has been performed on aircraft composite structures, composite bridge decks and pressurized storage tanks as these applications inhibit a longer history of industrial use. Nonetheless, a small number of cited works on CFRP-strengthened concrete members appears in the literature, mainly utilizing techniques that are already well established and frequently applied in industrial testing. Examples include ultrasonic inspection of interfacial defects in laboratory environments [14], thermographic field inspection of carbon fiber column wraps [11] as well as stress and temperature effects by electrical resistance measurements [15]. Currently, suitability of other techniques, such as penetrant testing, radiographic imaging or optical methods remains largely unknown. This raises the question whether alternative methods are not being investigated upon their potential for this type of inspection simply because other methods have already gained high acceptance and a stage of extensive industrial development. In contrast, methods may have already proven to be unsuitable for in-situ inspection due to safety issues or unjustifiably high cost. Lastly, as mentioned earlier, the unique material constellation found in rehabilitated infrastructure might favor new techniques that have not been previously been explored.

From a standpoint of practicality, only techniques that allow portability could be a potential candidate for field application. Clearly, in-situ methods must provide rapid testing, both with respect to inspection time as well as data acquisition and interpretation. Ideally, the method should be capable of locating defects on a global level to allow the rapid localization of defects over large areas while retaining relatively high sensitivity to localized discontinuities.

1.5 NDT ON REHABILITATED INFRASTRUCTURE

As addressed in the foregoing section, part thickness plays largely into defining the limitations of an individual NDT methodology. As a result, many techniques are restricted to surface or near-surface inspection. However, this does not imply that they are entirely incapable of revealing any information on subsurface properties. Instead, materials are often capable often revealing significant information about their subsurface nature by application of external stresses. With particular focus on CFRP-rehabilitated concrete components, a brief review of the particular material and dimensional configurations found in this kind of application will be provided. This will assure familiarity with some important NDE-related parameters, which is indispensable for the subsequent discussion.

For a majority of structural rehabilitation applications, CFRP is applied to a mechanically abraded concrete substrate. As such, the formed hybrid resembles a material of inherently different composition compared to most other NDT materials. Also, a majority of concrete components are of significant thickness, implying the necessity to inspect from only a single side of an individual member. Considering the use of concrete members in civil applications, component thickness rarely falls short of several inches, indicating that so-called “through transmission” techniques are either unsuitable or must be highly energetic to remain applicable.

In addition to former restrictions, which are mainly imposed by the base material, the composite overlay itself entails a number of restricting characteristics. Firstly, the material is oftentimes applied via the wet lay-up process, which tends to result in a composition of inferior quality compared to laminates manufactured under controlled environments or of higher automation (pultrusion, RTM, etc.). Surface irregularities, lower uniformity, and highly irregular concrete-composite interfacial bondlines are some of the consequences, resulting in additional difficulties during inspection. A generally favorable characteristic of external strengthening systems is the low thickness of the overlaid material. In most applications, laminate thickness remains below 2-3 mm, which might lessen or eliminate several difficulties otherwise linked to inspection of thick composites.

1.6 CAPABILITIES AND LIMITATIONS OF NDT

To successfully perform non-destructive testing of composite parts, its capabilities and limitations must be well understood and considered when analyzing the soundness of materials. Even though NDT techniques are in theory capable of providing information about specific material properties, they do not give an absolute indication on whether a material will perform well or fail in the near future. This is a common misconception and must be considered when performing NDT. It is thus essential that limitations of each test method be known prior to application [6].

Similarly, sensitivity and depth propagation of the method can significantly affect test results. If parts are extremely thick, attenuation can result in signal loss and restrict the inspection of lower regions of laminates. Due to a minimum detectable defect size that is typically unique to each test method, defects below such threshold might go undetected. However, this does not indicate that the part is defect-free. It simply constitutes that inspected region do not contain defects of equal or larger size than those of smallest detectable dimension. Also, qualification of inspectors to perform a specific type of test plays largely into validity of the result. If a single method does not provide comprehensive information to characterize a part as mechanically sound, a second, supplementary technique must be employed.

It is the intent of this report to review and discuss a variety of NDT techniques, most of which can be potential candidates for non-destructive inspection and characterization of laminated carbon fiber reinforced composite materials. Eventually, techniques will be evaluated based on their capability to detect defects that were discussed in part 1 of this report series. Techniques known to have significant drawbacks on either CFRP or concrete will be classified as unsuitable. Moreover, a considerable amount of previous work in a field will be valued preferable, since these techniques can be categorized as relatively well established. Also, equipment will most likely be at a higher level of sophistication and more readily available for further practical study, which further yields lower initial equipment cost and higher availability.

Preferably, potential techniques shall allow the detection of a variety of defects in both near-field and full-field manner. In addition, susceptibility to environmental changes can cause inconsistent results and must be classified as a drawback. All previous considered, the present report provides the reader with a preliminary assessment of techniques. It should be pointed out that assessment of applicability to field use cannot necessarily be derived from this information and must yet be confirmed through further investigation. To date, most research has been conducted on individual CFRP elements that have not been adhesively bonded to concrete substrates. It must be assumed that adhering CFRP to concrete will diminish suitability of some NDT methods that are otherwise well suited for inspection of composite materials. In contrast, the material composition and specific mechanisms found in rehabilitated infrastructure might favor techniques that have not yet attracted significant interest.

1.7 OUTLINE OF REPORT

To develop an understanding of non-destructive testing and its applicability to inspection of CFRP-rehabilitated structural components, the present report will be divided into three categories. These include

- Methods that have been applied extensively for inspection of CFRP-rehabilitated concrete components (Chapters 2 and 3)
- Methods, which are considered 'traditional' NDT methods, but have not yet found particular attention in the field of CFRP-rehabilitated infrastructure (Chapters 4-12)
- Methods that have already been applied to test and subsequently evaluate structures and their current state of performance (Chapters 13-15). Moreover, some of these methods have recently been suggested for inspecting the soundness of CFRP-rehabilitation schemes. However, they are typically not considered NDT techniques, as they mostly serve data-collection purposes. A subsequent analytical methodology is then applied to evaluate overall structural integrity

In conclusion, Chapter 16 discusses and subsequently classifies/ranks methods based on findings of Chapters 2-15. Classification of methods will be provided in tabular format to serve easier comparison of methods and allow a clear understanding of relative capabilities and limitations of each individual method. Primary attention will be given to defect-detectability as well as practical aspects, as these are paramount objectives in finding a suitable non-destructive field methodology. Although adequate defect-detectability should be assumed to be of high importance, methods of low flexibility, portability restrictions, extensive complexity or unjustifiably high equipment- and service expenses will not be of significance for further investigation. Only methods that show significant potential in regards to both theoretical and practical aspects will be considered favorable for implementation into NDE concepts for future establishment of structural rehabilitation quality standards.

2 VISUAL INSPECTION

2.1 FUNDAMENTALS AND THEORY

Visual inspection (VT) is used in virtually all fields of construction, including preparation, assembly and service, making it the most versatile yet simplistic technique. At all stages, personnel use their own judgment whether a procedure was followed correctly and if quality standards are being met. It may have been due to this triviality that VT was the last method to be formally acknowledged as a non-destructive testing technique [6]. While VT typically limits the observer to examine surface discontinuities - unless one inspects transparent or translucent surfaces - the effect of internal defects may sometimes cause deformations or discoloration of the surface, thus indicating a material deficiency. The field of visual testing encompasses a wide range of separate methods, which can be broadly divided into direct and remote techniques.

Direct Visual Testing: This form of visual testing is defined as a method where mirrors, telescopes or cameras are utilized. Direct examination is conducted if the observer can obtain access to be within 25 in of the object, and at an angle of no less than 30° to the surface.

Remote Visual Testing: Remote visual testing can be divided into three categories: borescopes, fiberscopes, and video technology. These tools allow for inspection of surfaces that are not directly accessible to the human eye. Use of flexible glass fibers permits the viewer to inspect images in great detail without causing much interference to the object. The incorporation of digital video cameras through use of solid-state imaging sensors, some of which are known as charge-coupled devices (CCD), allow for the display of images on a monitor. Advanced application for remote inspection via optical fibers will be discussed in more detail in Chapter 12.

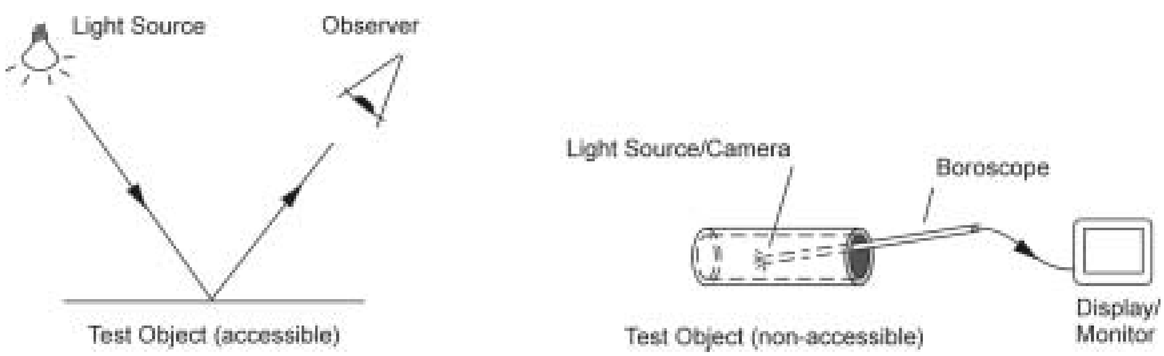


Figure 2-1: Direct- and remote visual testing techniques

Independent of method, all NDE techniques eventually rely on the efficiency of the human eye. When using the direct visual method, adequate light intensity must be given to retain visual perception to contrast and color, since a certain minimum level of light must be present for the human eye to produce an image. Other factors influencing vision are brightness, surface conditions, temperature, size and shape, as well as surface texture.

As such, cracks are more readily visible on smooth, bright surfaces where the relative difference between shape and color cause this type of discontinuity to stand out from its surrounding.

2.2 INSTRUMENTATION

2.2.1 DIRECT VISUAL

Clearly, the most important instrument is the human eye itself. As mentioned previously, the eye might need assistance in visualizing objects under difficult conditions, such as low light intensity or disadvantageous surface textures. To enhance visibility, magnifying lenses can be used to obtain a larger image, while auxiliary light sources, such as hand-held flashlights can improve image illumination and contrast. To collect data of examined parts, a multitude of measuring devices are available. The most common tools include calipers, gauges, templates, micrometers and other miscellaneous devices.

2.2.2 REMOTE VISUAL

In situations where the human eye cannot capture an image directly from the object source, remote examination must be performed. Devices used for remote imaging typically provide additional light to areas of low illumination as well as a magnifying effect of extremely small details that are otherwise indistinguishable to the eye. In addition, when the eye cannot obtain an unobstructed view, remote sensing becomes extremely important. For instance, fiber cameras utilize a light guide (fiberoptic bundle) to send light from the source inside an enclosed area to a CCD device for conversion to an electronic signal, which can later be displayed on a screen for further analysis. Also, large-scale examination is performed via use of conventional video cameras, which differ from the previous example in that they utilize a lens instead of a fiberoptic bundle to capture the image and transfer it to the CCD device. Here, remote visual sensing can be utilized to reduce the field of view, whereas fiberoptic bundles are used for magnification.

Regardless of application, these devices are always used to convert a captured image into a format that is more easily observable and interpretable for the examiner.

2.3 TECHNIQUES AND APPLICATIONS

When performing visual inspection, regardless of its specific type, inspectors are required to have a general understanding of what shall be considered as being a material anomaly. Evaluation, as all comparative techniques, is performed on a basis of comparing two or more objects with respect to their appearance. This includes size, shape, color, surface texture, etc. Hence, sound regions will serve as a baseline to those that may be of inferior quality. As we are familiar through everyday live, inspections are initially performed on a global basis to check for any obvious and outstanding differences. Once an overall baseline has been established, local checks are performed.

Visual inspection is used in virtually all aspects of health monitoring of composite rehabilitated structures. Currently, defectiveness and overall integrity of composite overlays are still assessed by this simple and cost-effective method. If visual inspection reveals certain surface deficiencies, inspectors may be able to comment on subsurface conditions and initiate further investigation using tools of higher sophistication.

2.4 CAPABILITIES AND LIMITATIONS

As has been discussed, visual inspection is a fast, convenient and inexpensive method to characterize the appearance of repair schemes in view of global and local soundness, aided through use of a variety of tools, such as magnifying lenses, auxiliary lighting or digital recording devices. One of the main advantages of visual inspection is the real-time acquisition of data and its instantaneous interpretation. Given the extremely low equipment cost, this inspection technique should be regarded as an indispensable precondition for all further investigations. However, access to and illumination of the object or area of interest is a major restriction of this technique. Moreover, it is limited only to the object surface. While obstructed views or acquisition of multiple images simultaneously can be realized though use of recording devices, subsurface conditions of opaque materials cannot be revealed.

Other drawbacks of VT are the high susceptibility to human misperception and the requirement for establishing of a baseline for defects in general, especially under varying conditions (i.e. time of day when inspection is performed, lighting conditions, inspector’s past experience, etc.). Consequently, examination procedures must follow inspection codes to ensure comparable results. On the other hand, although a thorough investigation is essential for quality control, overly particulate inspection of minor discontinuities can result in a time-consuming inspection procedure.

Summarized, visual inspection can provide rapid information on overall health of a structure and should thus be performed prior to initiating any further inspection processes. However, inspectors should understand its apparent limitations such that assessment does not lead to erroneous assumptions. Given this knowledge, visual inspection can serve as a highly effective supplementary NDE method.

3 ACOUSTIC IMPACT TESTING

3.1 FUNDAMENTALS AND THEORY

Mechanics of the acoustic impact technique (AIT) are based on the premise that assumes alteration of local stiffness of a laminated material by presence of a defective region [16]. Interestingly, it is one of the few methods that have found successfully application at two distinctly different levels of sophistication. In the basic approach, a hard, hand-held object (e.g. coin, miniature impact hammer, etc.) is used to impact the test object, as shown in Figure 3-1. In industry, the method is often referred to as the *coin tap test* [16]. Its methodology is based on the fact that if two materials that are bonded together are impacted with a small, hard object, the sound emanated will vary depending on the bond-quality of each tapped region. Over good regions, where there is an intimate bond between either composite or substrate and individual layers of fabric, tapping will cause a “full” sound whereas defective (e.g. unbonded) regions will result in a hollow response. This phenomenon is based on a localized reduction in stiffness above regions of disbonds, causing a difference in frequency excitation [17]. As a result, frequencies over bonded areas are perceptible as low-frequency sound, whereas unbonded areas respond with higher frequencies [16]. While this is true for localized defects, where the debonded region acts like an independent membrane, global softening, a phenomenon that rarely occurs in civil structures containing localized material discontinuities, would result in just the opposite effect.

Although the tap test is a real-time inspection method that provides the inspector with immediate results on subsurface anomalies, its efficiency is largely dependent on experience in signal interpretation. Similar to visual inspection, a persistent baseline must be established that constitutes characteristics of good signals comparative to those indicative of an anomaly, simply based on their response to impact. Since the method is non-automated, consistency of tapping force, -angle and -equipment are potential sources of variation. As such, the most significant drawback of the method has been operator dependency [16].

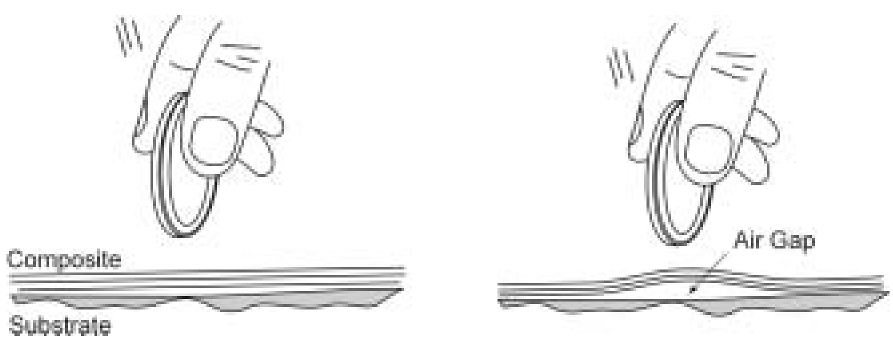


Figure 3-1: Coin-tap test

To enhance reliability of the AIT method, a more sophisticated form of impact testing can be utilized. Here, the motivation is to obtain more control over impact energy while recording the signal response to a more accurate and consistent level. Although the method is theoretically analogous to the tap procedure, the experimental configuration varies significantly. Both input force and signal response are recorded by means of digitalization and subsequent analysis on the basis of fixed evaluation parameters. Thus, variation in signal interpretation can be reduced.

In a generalized setup configuration of the AIT method, the manually induced impact force of the tap test is substituted by a mini-shaker, which is excited in form of a sinusoidal signal that is delivered from a power amplifier. A gauge is connected to the impacter-head to measure the force amplitude and time duration of the response signal. By further performing a Fourier transform on the force-time history, frequency content can be obtained [18]. Signal interpretation is derived from the fact that the contact stiffness is reduced in regions of delamination, which will cause a corresponding reduction in force amplitude. Further, a signal collected from a delaminated region is likely to show an overall broadening of the pulse width, i.e. longer pulse duration. A typical graph obtained from good and delaminated regions within a multi-layered carbon-epoxy laminate is shown in Figure 3-2. Given such information, the user can comment on subsurface quality in a more quantitative manner as compared to the coin tap method.

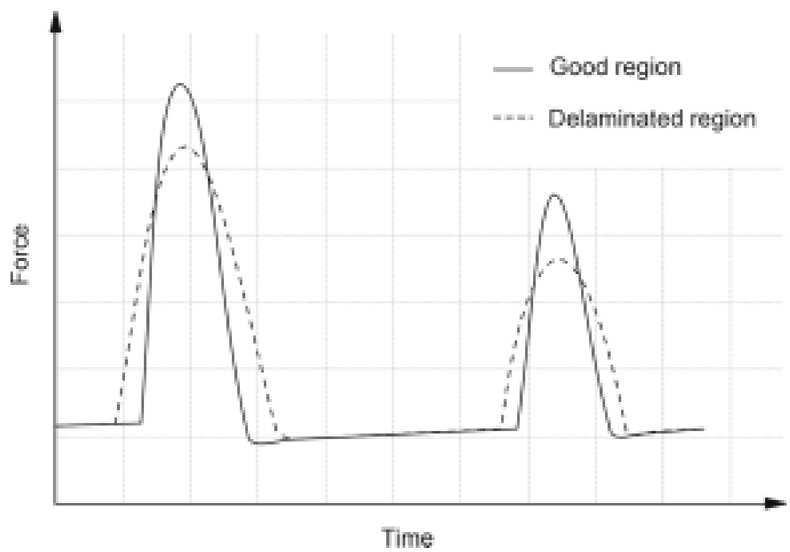


Figure 3-2: Force-time history in AIT testing (arbitrary untis)

3.2 Instrumentation

Apart from audible perception as well as a suitable object for impacting of local areas, the tap test does not utilize any type of sophisticated instrumentation. In force-time history analyses, however, instruments must allow distinct excitation and acquisition of the corresponding force amplitude. For this, a number of commercially available products have been used in industry. These include the Mitsui “Woodpecker” advocated by Airbus as well as the WichiTech “RD3” instrumented hammer, a commercially developed apparatus used at Boeing [19]. Both tools operate by using solenoid and hand-wielded hammers to measure the output of an accelerometer embedded in the hammer head (Figure 3-3).

3.3 TECHNIQUES AND APPLICATIONS

The simplest and most rapid AIT approach uses audible perception exclusively, not implying that this method is less suitable or must necessarily result in lower accuracy. Experienced personnel may be equally efficient in using a coin to tap surfaces for defects as someone trying to extract and evaluate data from instrumented impact devices. Similar to visual inspection, good hearing and sense for differentiating between audio signals are prerequisites for the manual form of AIT, since no data is being recorded for subsequent interpretation. A very limited number of research investigations have been conducted on manually induced impact response from CFRP-rehabilitated infrastructure components. This might be due to the fact that the method is difficult to instrument unless microphones or accelerometers are used to acquire frequency-time or force/acceleration-time histories. Much rather, due to the rapid procedure, it has been around to complement other methods.

Conversely, the instrumented version of AIT has been used excessively on composite components, such as honeycomb panels and graphite fiber reinforced composite laminates [20], [18]. Raju [20] focused on identification of defects in graphite-epoxy and graphite phenolic specimens, manufactured form twelve plies of prepreg (t = 1.9 mm) and six layers of carbon fabric (t = 1 mm), respectively. Herein, delamination was induced between the 5th and 6th ply of the graphite-epoxy composite. Also, fiber breakage and misalignment, induced during the layup process and located in layers 2 through 5 of the graphite phenolic specimens, were studied. A striker was used to apply an input force at a rate of 3 taps/s. Results indicated that delamination could be easily identified from differences in pulse duration between good and defective specimens. In contrast, force-time history analysis was insufficient to comment on presence of fiber misalignment and fiber breakage in the six-layered hand layup specimens. Instead, acoustic emission sensors (see Chapter 11) were required to extract multiple frequency components.

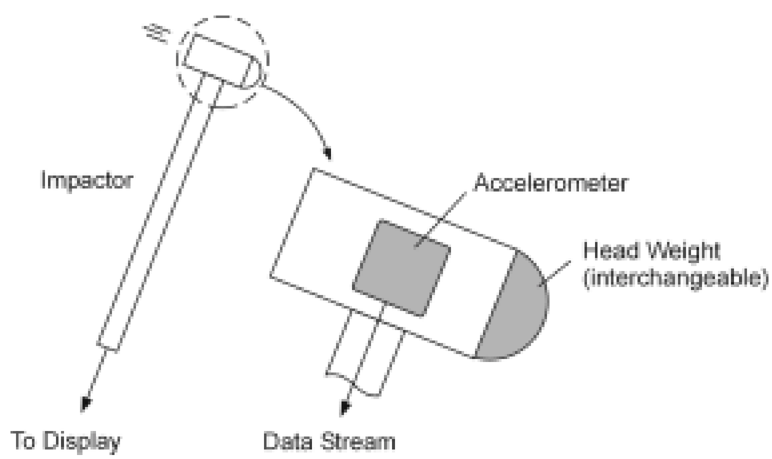


Figure 3-3: Common AIT impact device

Reports from reference [18] provide further confirmation for these results. Herein, carbon-epoxy composite specimens comprised of 19-20 layers of carbon prepreg, oriented at various angles were investigated via AIT. The artificially implanted material anomalies included delaminations, impact damage (resulting in a combination of delamination, debonding and matrix cracking), as well as 90-day moisture exposure. The test setup was mostly identical to that utilized in [20]. It was shown that AIT is highly sensitive to delamination as localized as 0.254 mm^2, especially if situated close to the part surface. However, adequate quantification of the extent of damage was limited to areas less than 160 mm^2. Beyond that, no further significant change in force-amplitude signal was observed. Similarly, due to the presence of subsurface delamination, regions of impact damage could also be located using the previously described AIT setup. However, AIT did neither appear to be sensitive to moisture-induced damage, nor shape or position of delamination along the width of specimens.

3.4 Capabilities and Limitations

In manual tap tests, differentiation between individual acoustic responses represents one of the main challenges of AIT. It remains largely subjective to operator interpretation and may cause considerable confusion, especially if a certain level of ambient noise is experienced at the site. Thus, operator dependency remains one of the major drawbacks of this form of AIT [19]. Furthermore, due to the low sensitivity in human audible sensing, the tapping method lacks sensitivity to small defects, such as porosity or fiber breakage. Nonetheless, it has proven to be quite suitable as a supplementary method to visual or other forms of examination, as it can provide rapid insight to medium to large subsurface deficiencies.

Through the development of specific tapping devices, some of the previous limitations of AIT could be reduced or eliminated. Because of a more controlled tapping force, frequency and incident angle, as well incorporation of force-time history analyzers, data interpretation is no longer susceptible to subjectivity. Also, systems remain fairly compact and thus allow good transportability and handling in field environments.

From the earlier discussion, it was also shown that delamination of extremely small size can be detected, without the necessity of coupling the detector to the test part. As such, one may easily scan an impactor along the part surface, which further eliminates the risk of eventual chemical incompatibilities between coupling agents and the composite material.

Nonetheless, AIT remains largely a surface inspection method. This, however, may not be of great significance due to the generally low thickness of CFRP used in this kind of application. From the aspect of signal visualization, AIT is currently limited to display force-time or frequency spectra, exclusively. For defect detection, these signals require further interpretation from an experienced inspector. Since no ‘mapping’ or area-scanning feature is available, AIT testing renders signal interpretation more difficult, particularly for inexperienced personnel.

4 PENETRANT METHODS

4.1 FUNDAMENTALS AND THEORY

For long, dye penetration has been utilized to display discontinuities in nonporous solid materials, which can be virtually any metallic or non-metallic material. The basic principle of this method is based on capillary action, a phenomenon that allows liquids to be drawn into tight openings, like cracks, porosity, laps or seams due the high surface energies, which are present at such surfaces. Any liquid absorbed by these openings is then made visible by means of special chemicals and, if needed, enhanced by external illumination with lamps.

For dye penetrants, good 'wetability' is important to ensure penetration into extremely small surface irregularities. Poor wetability of a liquid occurs when the surface energy of the penetrant is relatively high, such that the difference in energy between the liquid and surface irregularities is not significantly large. In contrast, wetable penetrants have a low surface energy and are absorbed more easily by high-energy surface cracks. An effective way of determining wetability of liquids is measuring of the contact angle between the tangent of the contact point and the surface. A shallow angle represents low energies and therefore good penetration (Figure 4-1). Other important aspects are the dye concentrate and viscosity. While high concentration of dye pigments ensures good visibility, a low viscosity will reduce the amount of time that is required for the penetrant to effectively infiltrate the material. Typically, black lights are used to visualize regions where penetrant has accumulated [6].

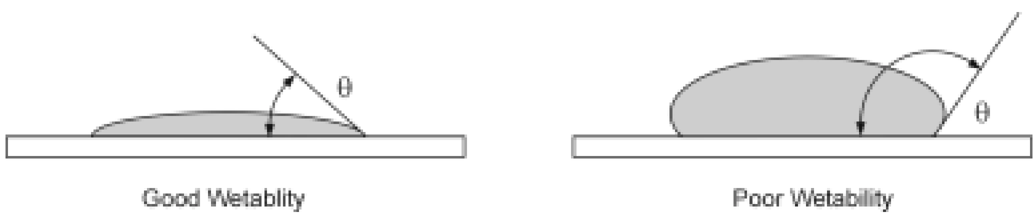


Figure 4-1: Wetability based on contact angle θ

4.2 INSTRUMENTATION

Penetrant systems can vary significantly in size and complexity. While a laboratory setup consists of multiple stages in an in-line arrangement, portable systems are available for use in the field. Systems typically consist of a precleaner, the penetrant liquid, some form of surface penetrant removal solution, a developer as well as a black light. Since these solutions can be supplied in small quantities, the method can be applied in virtually all in-situ situations.

4.3 TECHNIQUES AND APPLICATIONS

Successful use of penetrant techniques requires the inspector to follow a precise application scheme in order to ensure best visualization and contrast of any possible surface flaws. The application procedure, as shown schematically in Figure 4-2, can be summarized as follows:

- Precleaning and drying of the surface to be inspected
- Application of a suitable penetrant
- Removal of excess penetrant off the inspection surface
- Visualization of penetrant submerged in defects by use of developers
- Interpretation under black light or other comparable methods
- Post-cleaning to remove all surface residues

One essential step in penetrant testing is the thorough cleaning of the material surface. This must be done to ensure the unobstructed entry of penetrant into possible surface openings, which may otherwise be restricted by surface contaminants. Common forms of cleaning include solvents, ultrasonics, alkaline, steam, water and detergent or other chemicals.
On large parts that do not allow immersion in liquid baths or when hand application become too time consuming, penetrants can be sprayed over the entire area to provide complete wetting. Typically, penetrant imaging is used to detect defects in steel components, where crack formation is commonly found in the through-thickness direction and can therefore be detected. In contrast, composite materials tend to respond to impact or fatigue in form of delamination of interlaminar matrix cracking, both of which are undetectable using PT, as schematically shown in Figure 4-3. This may be the main reason why there has been little effort in utilizing this technique for non-destructive evaluation of laminated composite materials. For steel members, examples of successful applications include detection of leaks in tanks, tubings, welds and other components [21].

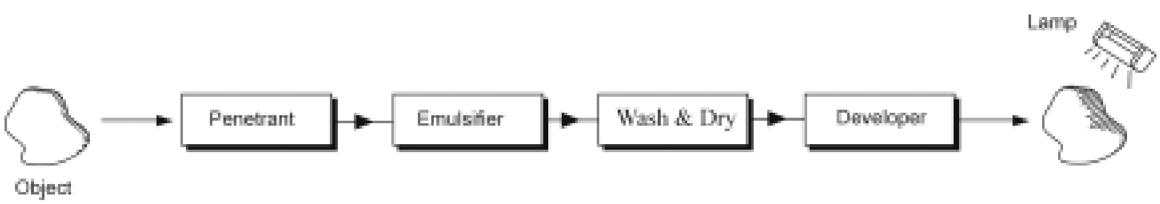


Figure 4-2: Procedural steps in dye penetrant inspection

4.4 CAPABILITIES AND LIMITATIONS

Penetrant testing is one of the best methods for locating surface discontinuities in solid, non-permeable materials. The rapid detection along with simplicity and high rate of coverage makes it a favorable technique for non-destructive inspection. Moreover, no electronic or sophisticated tooling is required. Also, penetrant systems are significantly less expensive compared to most other methods. Cost for standard systems comprised of penetrant, emulsifier, developer and evaluation tools, i.e. black light, rarely exceeds a few hundred dollars. Drawbacks of the method are obviously linked to the fact that only defects that reach the surface can be displayed. Delamination and debond of laminate layers are only detectable if they extend to the surface and allow seeping of penetrant into lower regions. Hence, a long but shallow surface scratch might appear to be more critical than a localized impact damage that may well have caused subsurface delamination throughout the laminate. In addition, the length of an external defect can be visualized, however, no information can be given on its depth [21]. Maybe the most significant drawback of penetrant methods is the difficulty of penetrant removal off rough surfaces [21]. It is known that composite materials, especially those processed by wet lay-up, typically show a significant roughness on their exposed surfaces. Consequently, penetrant tends to be trapped over the entire inspection surface causing irritating background fluorescence upon black light exposure.

Unlike many automated techniques, penetrant inspection uses chemicals to visualize material discontinuities, hence fluids that are flammable or volatile are potentially hazardous due to the likelihood of explosion or fire. If large amounts of substances like benzene or acetone are used, vapors that escape from open containers can ignite

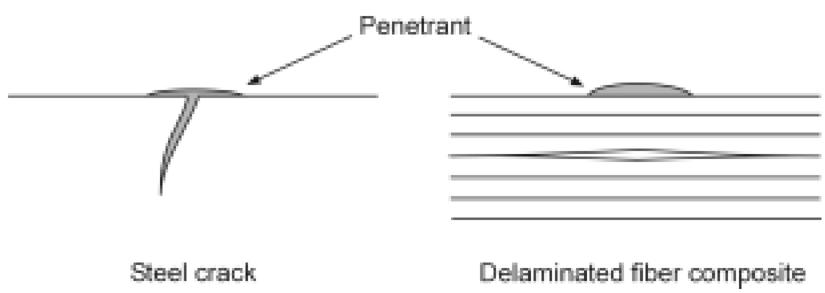


Figure 4-3: Differences in dye penetration between steel and laminates

5 ULTRASONICS

5.1 *FUNDAMENTALS AND THEORY*

5.1.1 WAVE PROPERTIES

In ultrasonic testing (UT), mechanical stress waves are utilized to detect internal material discontinuities. Mechanical waves propagate through material by means of particle oscillation, where motion within a material is carried out by particle motion that can be considered as discrete particles of mass, which are connected by springs. Wave propagation is largely depending on the type of excitation, mass of the individual particles as well as the spring stiffness of their individual connections. A wave, initiated by an external event such as normal or shear forces, travels by vibratory movement that is transmitted from particle to particle. If the springs that connect the particles would be infinitely stiff, all particles of the material would start to oscillate at the same instant and the wave would be transmitted at infinite speed. Hence, material elasticity and density play an important role in wave propagation. Former is related to the spring stiffness between particles, while latter describes the mass of the individual particles. Naturally, inertial forces restrict particles from being excited by their adjacent counterpart, thus, wave propagation occurs at a material-specific rate, termed as its *wave velocity*. A simple model of particle interaction is shown in Figure 5-1.

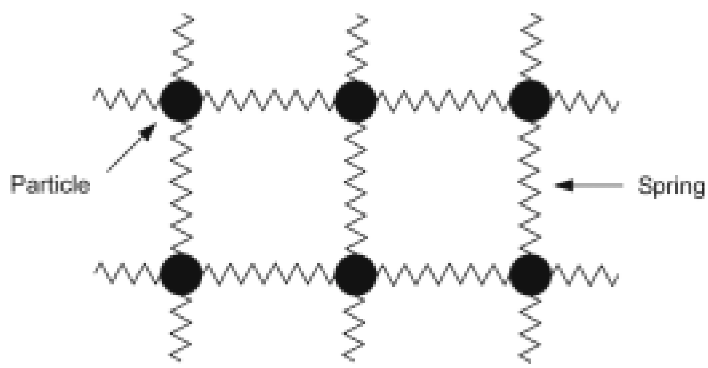


Figure 5-1: Particle interaction model[22]

While the above is applicable to solid materials, liquids or gaseous substances are not necessarily capable of transmitting certain forms of excitation to adjacent particles. Low-viscosity materials are often incapable of transmitting transverse excitations, whereas propagation of compressive forces remains possible. Common waveforms or *modes* that are utilized in ultrasonic testing are *compression waves* (longitudinal waves), *shear waves* (transverse waves), *surface waves* (Rayleigh waves) and *lamb waves* (plate waves). Compression waves are probably the most important form of wave that exists, since they form the waves for transmission of sound through air. Their particle oscillations occur in direction of wave propagation, causing compression of particles. Because solids, liquids, as well as gasses can resist compressive forces, longitudinal waves can travel in these media. Particle oscillation in shear waves occurs perpendicular to the direction of propagation, hence the material must be capable of resisting shear forces. Since this is only true for solids and certain liquids (of preferably high viscosity), all gaseous substances are incapable of transmitting shear waves. *Rayleigh*- and *lamb waves* are created when a compressive wave hits an interface and is consequently forced into *mode conversion*, as discussed in Section 5.1.2. Both wave types travel in form of elliptical oscillations along the surface of a material. Lamb waves, however, are more likely to occur in thin materials, such as plates or shells [22], [6]. Examples of the different waveforms are depicted in Figure 5-2.

5.1.2 WAVES AT BOUNDARIES

Since no substance extends over infinite space, waves propagating through a material eventually encounter material boundaries. If an incident wave encounters a material boundary, wave propagation is disturbed and wave characteristics are most likely altered. Although of rare occurrence, waves can hit an interface perfectly perpendicular, in which case neither mode conversion nor deviation from the initial propagation path will occur. Because the wave mode will not be altered, a compressive incident wave will transmit and reflect in the same compressive mode. In most cases, waves will encounter boundaries at some off-perpendicular angle, referred to as the *angle of incidence*. While this angle is taken to be 0° in case of perfectly perpendicular incidence, it can range from 0° to 90° for all other cases. At the boundary, part of the wave will be reflected at an angle equal to the angle of incidence, while some fraction of the wave will transmit into the second medium and *refract* (Figure 5-3). This phenomenon is described by Snell's law, which states

$$\frac{\sin i^\circ}{V_1} = \frac{\sin r^\circ}{V_2} \qquad (2)$$

indicating dependency of refraction angle on the ratio of wave velocity of the two materials.

A second phenomenon encountered at material boundaries is known as mode conversion, defining formation of new wave forms. The two most important material properties affecting mode conversion are the relative density and elasticity of the two materials through which the wave travels. They describe the *acoustic impedance, Z,* of materials, which in turn controls how much energy of the incident wave will be reflected at the boundary and how much is allowed to propagate into the adjacent material.

Although the incident wave may travel by means of particle compression, refracted shear waves can develop if boundaries are hit at angles other than 90º. At incidence angles nearly perpendicular to the surface, this effect is negligible, however, as the angle deviates more and more from 90°, the amplitude of the refracted shear wave begins to increase. With further increase in angle, the compression wave is refracted along the material boundary, i.e. it never crosses over into the second material. At this point only the refracted shear wave is present. In a similar fashion, the shear wave can be forced to propagate along the boundary, resulting in its disappearance. This specific type of mode conversion creates Rayleigh- and plate waves. They resemble an essential part in long distance UT detection techniques, since they are capable of traveling over far distances with substantially less susceptibility to attenuation. Detailed information on calculation of wave parameters is can be found in references [22], [6].

Although the velocity for each of the waveforms discussed in Section 5.1.1 can theoretically be calculated, it requires the precise knowledge of all material parameters, including any variation in homogeneity throughout the material. Because this is difficult to obtain, it is more standard to perform a *calibration* procedure in which the timebase of the detector is adjusted against a calibration sample [6]. This, however, presupposes that the user is provided with a material of identical thickness and composition as that under inspection.

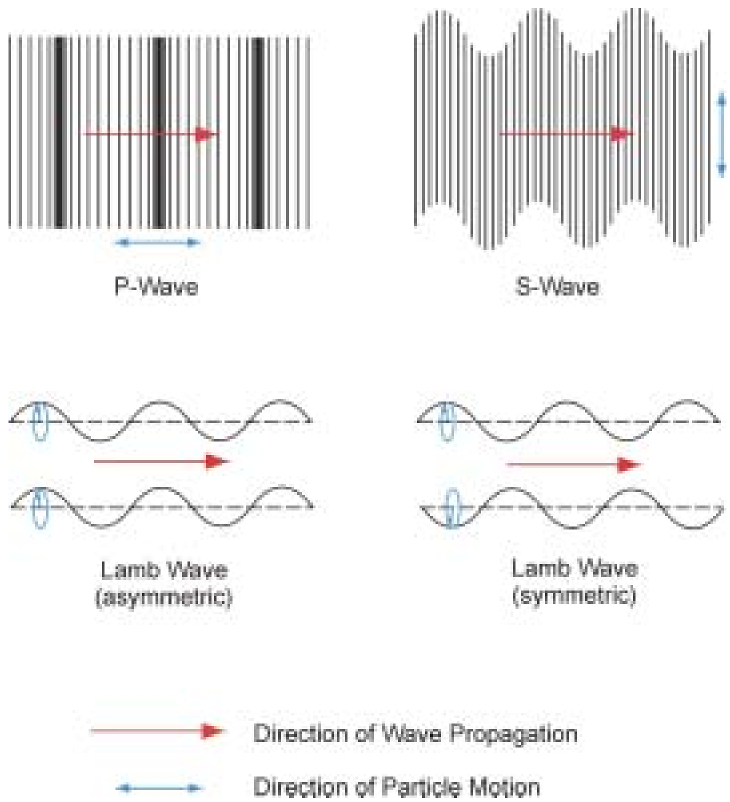


Figure 5-2: Propagation of common wave forms

5.1.3 DEFECT DETECTION

As mentioned earlier, incident wave fronts experience reflection at boundaries of differing acoustic impedance. It is this interfacial property that allows the detection of discontinuities in materials. Most defects, such as delamination, moisture or air pockets resemble a finite volume of air or water, entrapped inside the host material, whose acoustic impedance is significantly different from its surrounding. The percentage of acoustic energy that is reflected at a material boundary is given by

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad (3)$$

$$\text{with } Z_i = \rho_i \cdot V_i \qquad (4)$$

Here, R is termed the *coefficient of reflection*. Considering the difference in acoustic impedance between epoxy resins ($Z_2 = 2.7\text{-}3.6\ kg/m^2s$) and air ($Z_1 = 0.0004\ kg/m^2s$), one learns that the coefficient of reflection at a boundary of these two materials is roughly 1. Hence, due to the large mismatch in acoustic impedance, a nearly perfect reflection can be obtained at a composite/air interface. In a similar fashion, moisure, chemicals and physical inclusions are examples where acoustic mismatch allows their detection. It should be noted that these defects are only detectable as long as a finite volume of air is present between two adjacent plies. If materials are in intimate contact but completely unbonded so that no tensile or shear forces can be transmitted, an infinitely small volume of air is present that can often not be detected by UT. In these cases, other characteristic features of UT can be enployed to allow detection of these more critical anomalies.

5.1.4 Attenuation

Unless a material is perfectly homogeneous, slight variations in material density will cause permanent fluctuations in acoustic impedance in that specific region. While the difference of acoustic impedance can be used to detect discontinuous areas, it can also cause a disadvantageous effect in most materials, which is experienced in form of scattering or true absorption of the ultrasonic signal. Both these effects are combined in the term *attenuation*, which causes a more rapid loss in ultrasonic signal than that caused by pure spreading of a spherical wave. Generally, attenuation is dependent on the homogeneity of a material. Although metals can be assumed to have high homogeneity, variations in crystalline structure are sufficient to cause noticeable attenuation. Naturally, composite materials contain an almost infinite number of these discontinuities, mostly in form of matrix porosity and fiber-matrix interfacial regions. Moreover, attenuation is not felt equally in all directions in a composite material, since fibers are typically arranged in one or multiple principal directions.

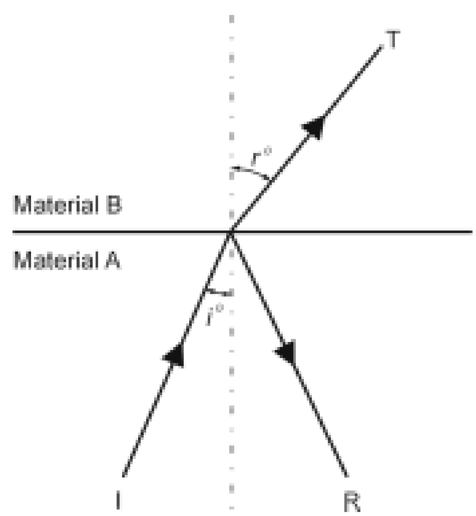


Figure 5-3: Geometric relationship between Incident- (I), Reflected- (R), and Transmitted (T) wave

Apart from acoustic impedance, the ratio of particle size to ultrasonic wavelength plays an important role in how the approaching wave front is attenuated. If the material is very coarse and its particle size is comparable to the wavelength, refraction, as described in Section 5.1.2, occurs at virtually every boundary. Once the wavelength is significantly longer than the particle size, waves are no longer geometrically divided. Instead, scattering occurs.

In conclusion, if testing anisotropic composite materials, one should give preference to longer wavelengths, i.e. excite the material at lower frequency. However, as the wavelength increases, sensitivity to small defects rapidly decreases, due to the fact that waves are no longer reflected at boundaries but much rather scattered [14]. Hence, frequency selection in UT inspection of laminated composite materials is usually a tradeoff between attenuation and sensitivity.

5.2 INSTRUMENTATION

A variety of ultrasonic detection devices are available as portable units, consisting of one or more ultrasonic transducers and a control unit. Today, most portable units are no larger than 11 x 6 in (compare Figure 5-4) and encompass the entire palette of controls required for ultrasonic testing, including signal pulsing and detection, amplification and signal display. Most units can be battery operated and allow inspection with high flexibility.

Figure 5-4: Portable UT unit

5.2.1 TRANSDUCER

An ultrasonic transducer, also referred to as *probe*, is responsible for emitting and receiving mechanical waves. Its primary function is to convert an electric signal into a mechanical impulse and vice versa. Use of the piezoelectric effect in quartz crystals allows this type of conversion, where a high voltage spike causes expansion or contraction of the crystal, depending on polarity. Figure 5-5 depicts a schematic of the mode of operation for piezoelectric elements. Transducers can be composed of a single crystal, such that they can either transmit or receive a signal. Alternatively, dual transducers combine the possibility of sending and receiving mechanical signals simultaneously. To allow simultaneous inspection of broad areas, phased array transducer can be used. They incorporate a number of small piezoelectric elements that, under proper excitation, are capable of directing the acoustic beam at various angles. However, these transducers require a more advanced control unit that is capable of sending signals to each of the elements individually, such that acoustic beams can be sent out at predefined angles.

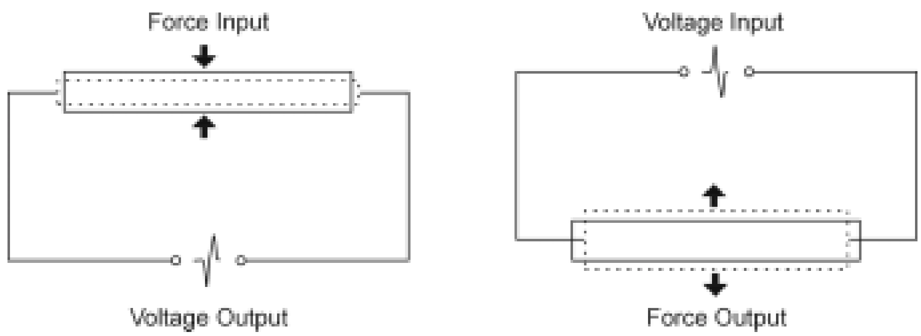


Figure 5-5: Piezoelectric element under mechanical stress (left) and voltage (right)

One of the most important specifications for UT testing is the frequency range at which transducers operate. Each transducer has a predetermined frequency based on their thickness. While each transducer tends to oscillate at its resonant frequency, a range of other frequencies are produced as well, ranging from slightly lower to slightly above the resonant frequency. Also, to adjust to different thicknesses and surface textures of test specimens, transducers are available in various diameters. For inspections that require high accuracy and resolution, a smaller probe would be preferable. However, an important tradeoff of small probes is the usually large variations in signal amplitude due to increased sensitivity to surface roughness [23]. A common classification for transducers in UT is based on their excitation frequency. In practice, transducers utilizing excitation frequencies above 10 MHz are classified as high-frequency while those of frequencies lower than 10 MHz are regarded as low-frequency types. Transducers shown in Figure 5-6 utilize piezoelectric elements of about 1 inch in diameter and are specifically designed for pulse-echo inspection in conjunction with a *delay line* material. The delay line, which is comprised of material with acoustical properties similar to that of water, is coupled to the transducer wear surface through a thin film of glycerin and attached by means of a retainer ring. Impetus of utilizing the delay material lies in distancing the transducer's piezoelectric elements from the front surface of the inspected part, which enhances near-surface resolution.

5.2.2 CLOCK

To force the piezoelectric crystal into mechanical oscillation, a high voltage pulse is supplied at a certain repetition rate. A clock that is incorporated in the UT unit controls this frequency rate. It regulates the frequency of the exerted mechanical excitation, preferably in a range that allows penetration of the material without sacrificing much of the lower end of the sensitivity scale. In most modern systems, the excitation pulse can be generated in either spiked of square form. Generally, the spike pulser will yield better results when using high frequency transducers (see Section 5.2.1), whereas the square pulser generally performs best in combination with lower frequency probes.

5.2.3 RECEIVER/AMPLIFIER

The receiver is another component that is incorporated in the UT unit and is responsible for receiving the electrical signal from the transducer. To adjust the signal intensity such that it can be appropriately displayed on a screen, an amplifier is used to regulate the electrical signal.

Figure 5-6: Piezoelectric transducers

5.2.4 DISPLAY

Ultrasonic signals are normally displayed in an x-y coordinate system, with the x-axis linked to a time-base-trigger, while the y-axis is utilized to represent the energy that is received from a mechanical wave at the transducer. In its simplest form, information is displayed in form of an A-scan, where each image represents a spot-scan of the material. In regions where sound waves of high intensity are recorded, as would occur at a shallow discontinuity, peaks are displayed on the screen. Although this method of displaying data is fast, it simply provides a momentary spot image that is typically not recorded for further evaluation. A more sophisticated image can be acquired when performing B-scans. This method displays a cross-sectional view of the component by successively recording A-scans as the transducer is moved along a path over the test piece. Hence, a spot-image is recorded synchronously as the probe is moved over the specimen. Brightness of each location is dependent on the intensity of the received signal. If cross-sectional scanning is performed in a continuous grid pattern, a plan image or C-scan is obtained. C-scans are currently the most well suited method for fast and comprehensive testing of materials. Through modern systems and a variety of digital adjustments, as well as the possibility to transfer all acquired information to a PC, much information can be derived from a modern ultrasonic scan. Examples of typical A-, B-, and C-scans are shown in Figure 5-7.

In the left image, the transducer resides in a fixed location on the part and the graph obtained depicts the intensity of the received signal on its vertical axis, while time-of-flight is graphed along the horizontal axis. Reading the signal from left to right, the user obtains three distinct energy peaks that represent reflections off the front- defect- and backwall surface, respectively. In b), the transducer is swept along a straight line while successively recording A-scan data at preset time increments. From their relative intensity, changes in the A-scan profile can be transformed into various levels of grayscale. Due to the continuous stream of data, B-scans impose a significantly higher demand on recording and storage capability of the ultrasonic system. Finally, image c) shows a 'mapped' image of the subsurface anomaly, which is more or less a combination of B-scans, each taken from a slightly different section of the part. As these sections are recombined into one image, the defect perimeter becomes visible.

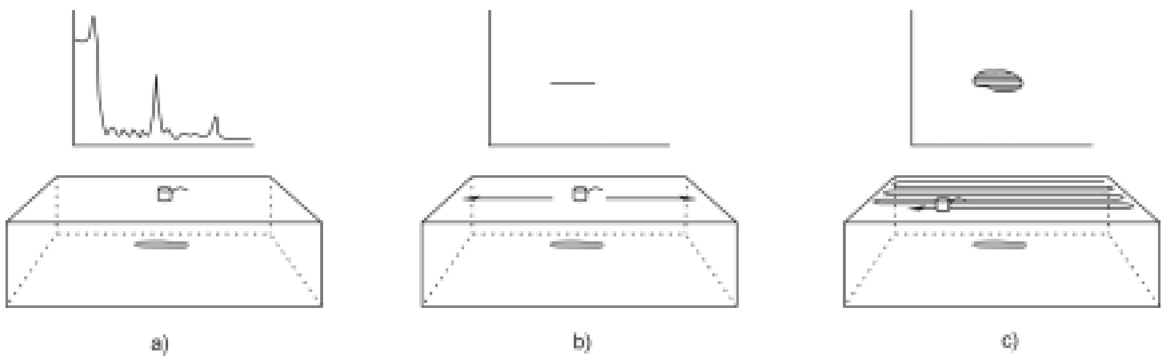


Figure 5-7: Idealized A-Scan (a), B-scan (b) and C-scan (c) of delamination

5.3 TECHNIQUES AND APPLICATIONS

Ultrasonic inspection is one of the most frequently used NDE methods today. It has found excessive use in the medical field as well as the civil- and aerospace industry. Most industrial applications aim at crack detection in airplane wing skins, defect detection on composite laminates or thickness measurements.

5.3.1 IMMERSION TESTING

Immersion testing is performed to ensure good and continuous *coupling* between the transducers and test piece. Although the impedance mismatch between water and most solid materials is of considerable magnitude, it has proven to transmit the sound waves much more efficiently than air. Furthermore, water immersion allows for a wide spectrum of incidence angles since the transducer must simply be tilted to the right angle without the need for wedges that connect the transducer surface to the surface of the test piece. An obvious disadvantage of this method is the need to immerse parts into a tank for inspection. Since this cannot be done with entire structures, water immersion is not suitable for structural inspection.

5.3.2 CONTACT VS. NON-CONTACT METHODS

Alternatively to immersion techniques, the transducer can be coupled to the test piece in a variety of other ways. To achieve adequate energy transfer and to minimize the acoustic impedance mismatch between the transducer and composite material, viscous gels, waxes or water jets (squirters) are commonly used as coupling agents. Although these forms of coupling allow for more flexibility compared to immersion testing, the user remains relatively restricted due to the requirement of continuous presence of a thin film between probe and sample surface.

Lately, the need to provide means of non-contact inspection has arisen, since this method promises a decrease in inspection time as well as a broader range of applications. The main advantage of air-coupled inspection lies where the inspected material or its subsequent processing is incompatible with the coupling media. Moreover, a near surface delamination may become filled by low-viscosity couplants and therefore be missed during inspection. However, the large mismatch in impedance between air and solids has been a limitation for such forms of testing [22]. It is known that, in comparison to water coupling, signal reductions of up to 140 dB are experienced [24]. Recently, through the use of electrostatic transducers with broader bandwidth, successful studies have been conducted using air-coupled techniques on composite laminate structures [25], [26]. In the following, a number of UT procedures from previous investigations are presented and evaluated towards their applicability to NDE of rehabilitated structures.

5.3.3 Through-Transmission Testing

In this form of testing, two transducers are positioned on either side of the inspected part. Due to a shadowing effect caused by internal material discontinuities, signals of different magnitude can be recorded on the opposite side of the test piece. This method has proven to be unsuitable for NDE of structures since high attenuation, linked to the large thicknesses of most structural components, rarely allows adequate transmission of ultrasonic signals.

5.3.4 Pulse-Echo Testing

5.3.4.1 Theory

In pulse-echo testing, access to only one side of the test piece is required since this method evaluates the echo of mechanical waves as they are reflected off interfaces inside the composite laminate. Such interfaces can be the front surface where the transducer is placed, the back surface of the composite strip as well as any internal defects of adequate size and orientation. Two forms of probes are commonly used in this technique, namely single and dual-crystal transducers. In the standard compression wave technique, ultrasonic energy is directed either perpendicular or near perpendicular into the test piece, such that an adequate amount of energy is transmitted into the test material. Unless air-coupled transducers can be used, a couplant that is compatible with the test material must be employed to ensure wave energy transfer. The time base of the UT display must be calibrated to at least one time the full scale to display the entire thickness of the test piece, as depicted in Figure 5-8. In a perfect material, two peaks will the seen in an A-scan image, which originate from the front surface and the far surface, assuming both are near perpendicular to the transducer. Two important features of the signal obtained form an A-scan are separation of peaks and signal clarity. Utilization of too low frequencies (directly related to large wavelengths) can cause interference between signals reflected off the front and rear surfaces of an object, a problem that is faced most frequently in thin materials. Again, a tradeoff between excitation frequency and attenuative properties of the material must be considered. Also, clarity of the recorded peaks will be mostly dependent on the material attenuation as well as the surface smoothness.

If the incident wave front encounters a delamination that is smaller than the transducer width, parts of the wave will be reflected back to the probe while parts of it will continue to travel towards the far surface. Depending on magnitude and location of the intermediate and far-surface peaks, predictions about size and depth of internal defects can be made.

In cases where the crack surface is not near perpendicular to the direction of wave travel, reflections will most likely be directed away from the transducer. Thus, no signal will be received and no predictions about internal defects can be made. Also, if defect size is much smaller than the probe diameter, the signal intensity exerted from a defect may be much smaller compared to that of the material interfaces. In this case, it will be necessary to increase the equipment gain to display any internal defects on the screen. In situations where defects propagate parallel to the direction of wave travel, as shown in Figure 5-9, only a weak signal will be reflected off the defect, thus predictions are often impossible.

With particular focus on bondline inspection between concrete and composites, the usually highly attenuating concrete surface diminishes most of the incident wave front and can contribute significantly to signal scattering. Consequently, noise instead of a clear backwall reflection will be recorded.

5.3.4.2 Applications

Successful applications of the pulse-echo technique have been reported by [14], [27], and [23]. Kundu et al. [14] can be named as one of the few references that discuss the detection of delamination between concrete and CFRP plates. In this study, a GCFRP plate, manufactured from three layers of [0/90] fabric was attached to a concrete substrate by means of adhesive bonding. The plate measured 3.66 mm in thickness, resulting in a total thickness of adhesive and plate of 4.56 mm. The artificially induced defect was in form of an air pocket of roughly 50 mm diameter located near the center of the concrete/composite interface.

Due to the negative effect of attenuation, low frequency excitation below 1 MHz had to be used in this study. It was found that at low frequencies, penetration deep into the material could be accomplished, however, pulses reflected off the front and rear surface were not well separated. Upon increasing the frequency to 5 MHz, attenuation reached levels at which almost no material penetration was possible. Such finding led to utilization of resonance properties of composite laminate. Due to destructive interference at multiples of the ultrasonic wavelength, a sharp drop in voltage amplitude vs. frequency response can be observed. If the apparatus is adjusted, such that this drop occurs in good regions of the material, any change in material constitution, as would be caused by a delamination or voids, will result in a shift or disappearance of this peak. From this, the observer can conclude a material discontinuity. Even though this technique has shown potential in finding defects, little is know about sensitivity to size or type of the particular anomaly. Further, any slight variation in plate thickness would also cause a change in resonance properties. As a result, false conclusions could be drawn.

One of the major difficulties in bond inspection via UT lies in the necessity to obtain clean back wall echoes from the interface where two materials are joined. To obtain a reflective signal of sufficient amplitude, the incident wave front must be reflected at a preferably flat interface. This, however, is rarely provided by concrete morphology, particularly in situations where surface roughness is considered advantageous for enhancing mechanical interlock. As a result, the incident wave front encounters a surface morphology that causes severe signal scatter that results in a considerable amount of background noise (Figure 5-10).

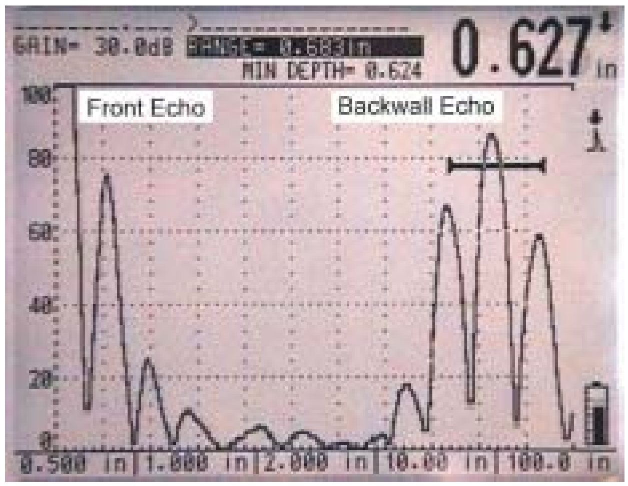


Figure 5-8: Calibration of display to 1x specimen thickness

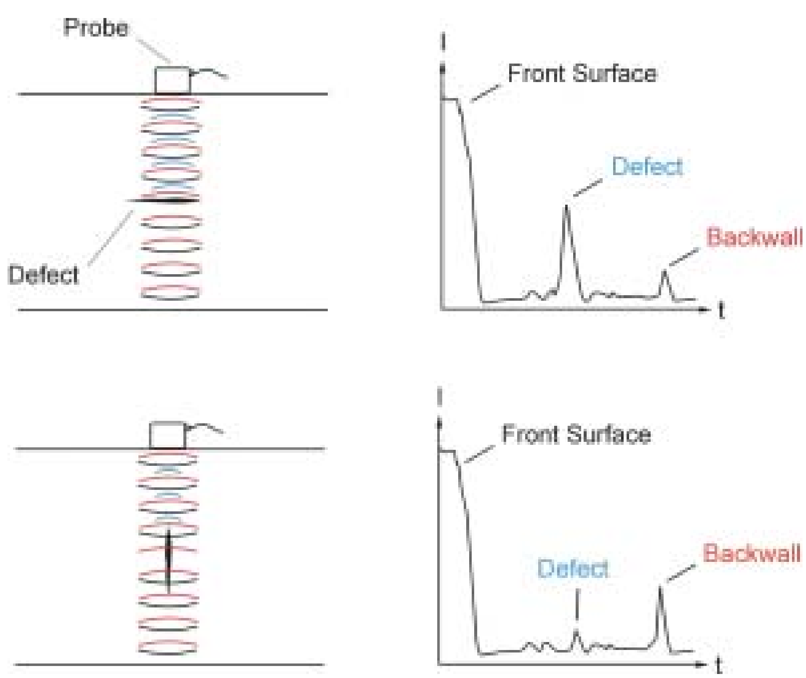


Figure 5-9: Reflection of stress waves off internal discontinuities

Scarponi and Briotti [27] conducted experiments on low-velocity impacted CFRP plates as they are typically found in aerospace applications. The NDE system was comprised of 5 and 15 MHz probes for emission and reception of the ultrasonic waves. Test results showed a successful use of even the high frequency 15 MHz probes that were able to detect both size and depth of the impact damage. While this is in contradiction to [14], the extremely high uniformity and consequently low attenuation of the aerospace CFRP components may have allowed the use of short wavelengths. This is a promising result for use of high-frequency UT on prefabricated strips, nonetheless, its applicability to wet lay-up should be reviewed more skeptically.
Summarized, normal incidence pulse echo inspection has limited applicability to concrete-bonded CFRP composites due to the high attenuating properties, lack of adequate resolution of reflected peaks, as well as the generally tedious procedure for large-area scanning.

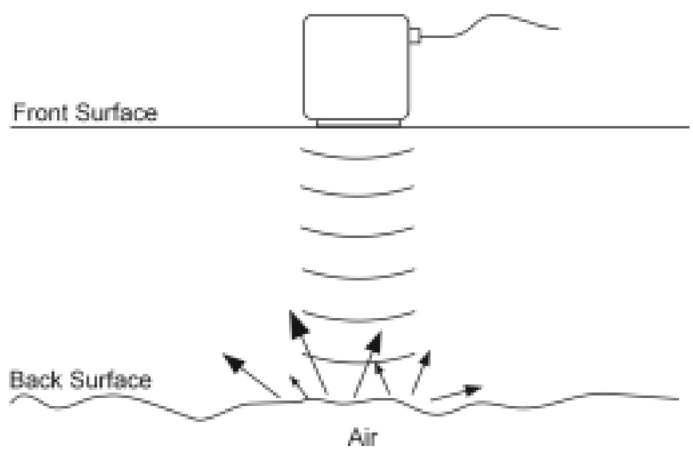


Figure 5-10: Signal scatter due to uneven surface morphology

5.3.5 *PLATE- AND LAMB WAVE TESTING*

5.3.5.1 *Theory*

Unlike propagation of normal incidence waves, lamb waves travel parallel to the test surface and have an elliptical particle motion. They are also referred to as *plate waves* or *guided waves*, indicating the possibility of predetermining their direction of travel. Lamb waves can solely be generated in materials that have thicknesses of only a few wavelengths, indicating their applicability to thin, plate-like objects. As a result, they have been used extensively for studying the wave propagation of thin composite laminates [2], [23], [28], [24].
To initiate lamb waves in a thin material, the incidence angle must be adjusted according to the specific frequency and material thickness. For use on composite materials, these angles are typically within the range of 17 to 25° [14]. Waves can be transferred into the test material by means of using perplex wedges or through air coupling. They can propagate at symmetric and asymmetric modes, commonly denoted as *S* and *A*, respectively. In the symmetric mode, energy is transferred in a similar manner to that of a compressive wave where the midplane of the plate remains stationary. In contrast,

shearing motion is predominant in asymmetrically propagation lamb waves, resulting in a flexural motion of the entire plate [29].
Interestingly, attenuation properties are significantly different between symmetric and asymmetric lamb waves. As such, the *A*-mode attenuates roughly eight times greater than the *S*-mode. Hence, the *S*-mode appears more attractive for large-area inspection [2]. Compared to normal incidence pulse echo, lamb waves are capable of traveling for significantly longer distances, often up to several meters. As a result, the path between two angled probes, placed at a fixed distance from each other, can be inspected rapidly using this technique. It can thus be concluded that lamb wave testing is more suitable for in-situ inspection of large areas than the more commonly used pulse-echo technique. Regarding sensitivity, the two methods can be viewed as complementary to each other. This is based on the fact that sensitivity of the lamb wave method reaches a maximum in regions where defects are situated closest to the surface. In contrast, the normal incidence method is highly sensitive to delaminated region located deeper in the material, assuming its material composition is fairly uniform. Fortunately, most UT equipment can be utilized for both normal incidence and lamb wave tests. Figure 5-11 illustrates the difference in test setup between normal incidence and guided wave testing.

5.3.5.2 Applications

Over the past years ultrasonic lamb wave testing has been utilized extensively, including inspection of adhesively bonded joints, delamination, porosity and fiber misalignment [30], [14], [24]. Furthermore, studies on detectability of impact- and thermal damage have shown promising results [31]. Such studies have shown several significant advantages of lamb waves over normal incidence testing for detection of a wide range of defects. These include an increased sensitivity to near surface defects, as they are naturally found in composites comprised of only a few layers, which makes lamb wave testing especially favorable for the current discussion.

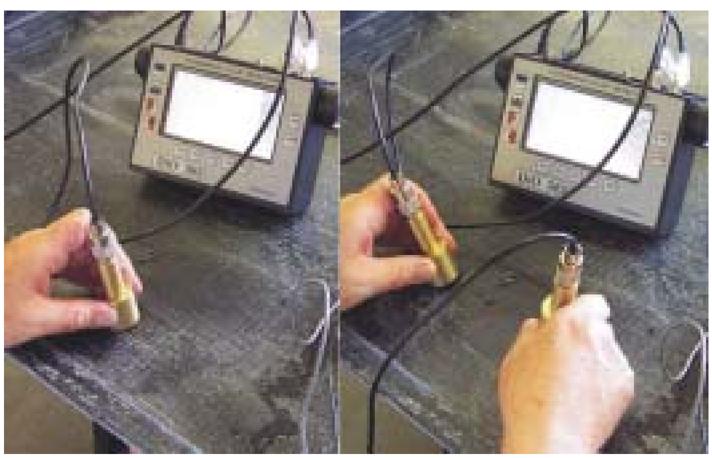


Figure 5-11: Test setup for normal incidence (left) and guided wave testing (right)

Since flaw detection through use of lamb waves is not based on their reflection off surfaces but much rather their alteration through presence of defects, two transducers

must be employed for testing. In a typical test setup, transducers are positioned at a fixed distance apart and at identical angles from the vertical axis. For inspection of longer distances, the surface of the test object is located in the defocus position, indicating that the axes of both transducers coincide below the test surface. If the defocus position is selected, the emitted signal that is reflected directly off the test surface cannot reach the receiving transducer. Instead, a *leaky* signal, which the wave emits as it travels along the plate, can be picked up by a second transducer and used for further interpretation.
Signal interpretation can generally be performed using one of the following three methods. Firstly, the attenuation caused by travel through a defective region can be interpreted. This is generally performed via amplitude monitoring of the received signal. It has been shown that determination of delamination depth is possible solely based on a drop in signal amplitude [23]. One example of such a drop in signal is caused when an incident lamb wave encounters a delamination situated near the surface, which results in separation of the wave. Most of the energy is attracted by thicker sections of the laminate (Figure 5-12). Consequently, if the wave signal were picked up just above a shallow delamination, a significant decrease in amplitude would be noticed. Secondly, reflections of *S*-modes, caused by interference of the incident lamb wave with defect boundaries, can be used to comment on possible material discontinuities. Lastly, mode conversions are potentially capable to provide information on presence of defects.

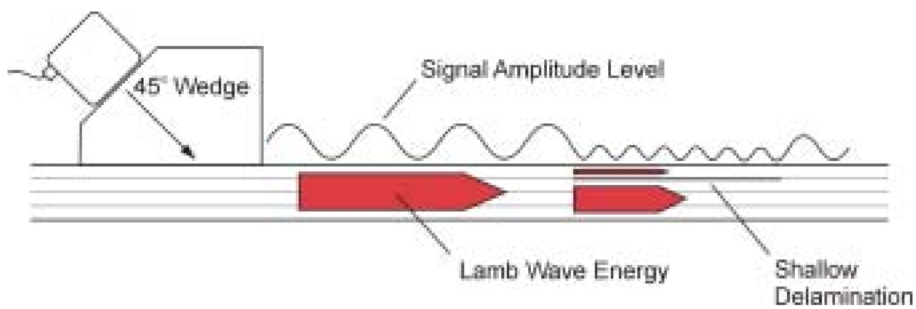


Figure 5-12: Lamb wave interaction near delaminations

Similar to C-scan imaging in normal incidence UT, results obtained from lamb wave analysis are displayed via so-called L-scans.

5.4 Capabilities and Limitations

Without question, UT has been the most frequently utilized method over the past decades. It has found wide acceptance in aerospace and manufacturing industry in general, mainly for use in quality control of welds or discontinuities in metallic or laminated composite parts. The method is capable of detecting a wide range of defects, including shallow and deep delamination in thin to medium laminates, porosity, and effects of environmental influences such as moisture accumulation or impact damage. Due to the continuous development of ultrasonic devices, the method can be classified as extremely portable with a wide variety of test equipment being readily available. Use of computer-aided signal filtering (DAC, TVG, and CSC) has shown to decrease sensitivity towards material variations, which makes the method even more applicable for field inspection. Although coupling to the test surface remains a delicate issue for field use, development of new transducers has lately opened advanced possibilities for air-coupled inspection [26]. Furthermore, UT allows part inspection from only one side, making it potentially suitable for defect detection in rehabilitated concrete structures. Using these techniques, most defects can be characterized in size and depth. Based on numerous sources, UT has been assessed as being one of the most versatile and promising NDE techniques available today [23], [32].

However, no single nondestructive testing method can be considered a panacea. UT signal interpretation is largely influenced by a number of variables, including defect orientation, ambient temperature, attenuation, surface conditions and choice of couplant. As mentioned earlier, the orientation of a defect relative to the direction of wave propagation is crucial to detectability. Although complementary methods are available to detect defects of multiple orientations, this can result in a time consuming inspection process. The same is true for inspection of large areas, especially when using spot scans obtained from pulse-echo testing.

When applied to composite laminates, a limitation called *shadowing effect* is often experienced. If examined from only one side, delaminations that occur near the surface may obscure those located deeper in the composite, a phenomenon that is commonly experienced in impacted specimens [33]. Also, reproducibility of the UT method is significantly reduced. The high attenuation caused by an almost infinite number of interfacial boundaries restricts the use of high frequency testing that is needed for adequate sensitivity. In many cases, the signal is not capable of penetrating deep into the material, because of disadvantageous surface conditions.

For in-situ inspection, environmental conditions can cause further variance of the results. Since temperature affects the velocity of sound in most materials, erroneous depth readings or refraction angles can be obtained. Thus, the possibility of changes in temperature must be considered when first calibrating the equipment. A specifically critical aspect for detection via UT is a so-called *cold* or *kissing bond*. These are regions where two materials are in intimate contact but do not possess any strength at their interface to resist tension or shear forces. This form of debond is not detectable via pulse echo UT since the encapsulated volume at the interface is of such infinitesimal size that virtually no acoustic impedance mismatch exists.

Concerning signal interpretation, the various forms of ultrasonic scans, namely A-, B-, and C-scans allows for a multitude of visualization options. However, it should be noted that C-scans can only be generated if the probe is scanned over a fixed x-y coordinate system in which the system receives distinct information on probe location at each instance in time. Cost for these systems is often extremely high (in excess of $100,000) and demands equipment of significantly higher sophistication, including continuous acquisition and storage of each data point along the x-y area scan. A much more cost efficient A-scan unit ($7,000 to $15,000) can generally perform identical inspection routines as the C-scan setup, however, it necessitates manual scanning of the entire area including real-time signal interpretation, which demands permanent attention of the inspector throughout the entire testing procedure.

Summarized, UT is capable of detecting a large number of material defects and has proven to be applicable for in-situ inspection for many years. Although certain difficulties arise when applied to composite materials, especially on those processed via manual lay-up, it must be appraised a potential candidate.

6 RADIOGRAPHIC TESTING

6.1 FUNDAMENTALS AND THEORY

Radiographic testing (RT) dates back to the discovery of x- and γ-rays in the late 19th century, which has led to tremendous advances in the field of medical examination as well as scientific testing. In general, radiographic imaging involves three components, including a radiation-emitting source, the specimen to be examined, and a recording device such as a suitable film or digitizing system. While radiographic films are typically covered with an emulsion that is chemically changed through ionization as radiation interacts with it, digital recording devices represent more convenient means of radiographic detection. In theoretical terms, radiographic energy is a form of electromagnetic radiation of extremely short wavelengths, where higher energy levels correspond to shorter wavelengths [34]. The important characteristic of radiation lies in the ability to penetrate most opaque materials while retaining a high percentage of its energy to produce an image on the opposite side of the test specimen. In the past, three main forms of radiation have been applied to nondestructive testing namely x-rays, γ-rays and neutrons.

X-rays are produced in a vacuum tube where high-speed electrons are focused at a target material, usually made of tungsten, and forced to interact with it. Such interaction results in the release of quantum energy, or *photons*, which are capable of penetrating solid matter. This ability to penetrate matter is related to the extremely short wavelength of electromagnetic radiation of x-rays, which is in the range from 10^{-6} to 10^{-10} cm (compare Figure 1-4). The applied voltage, typically expressed in kilovolts (kV) is the main governing factor for energy of the radiation. Most commercially applied units operate in the range of 100 to 400 kV [6]. For inspection purposes, an increase of radiation energy will cause shorter wavelengths and an increase in material penetration.

Unlike x-rays, γ-rays are emitted by unstable radioactive isotopes, which possess a so-called *half-life*. While the energy level of individual isotopes, such as cesium, iridium or radium, is unique to each material and remains a constant, intensity will decay with time. Since exposure is a function of intensity and time, the level required for adequate penetration of a material will not be achievable once a certain time period has passed. Thus, the isotope must be discarded and exchanged by a new source.

Neutrons, the sub-atomic particles, are not considered electromagnetic radiation. Instead, they are released by *particle sources* that can be in form of nuclear reactors, particle accelerators, or man-made radioactive materials. While reactors are highly regulated devices with limited access, particle accelerators have been available for laboratory testing and are quite small in size. Lastly, radioactive isotopes, such as californium-252, have been developed for small, simple and reliable operation [34].

While all success in radiographic imaging is governed by the capability of penetrating the test material, the penetrability of each of the previous forms of radiation is dependent on different parameters. For example, x-rays are not capable of penetrating high-density materials, which is why lead jackets are commonly used to shield humans from the emitted rays.

Material discontinuities can be detected via differences in absorption or attenuation rates as photons pass through the atomic structure of the test material. Similar to radiographic imaging of the human skeleton in medical x-ray, regions of higher material density typically allow for lower penetration of photons than their surroundings. Consequently, lighter appearances on the recording media will indicate the presence of more dense materials along the beam path. As such, porosity or other gaseous inclusions show as dark spots or lines. While a clear relationship between mass attenuation coefficient and material density does exist for photon penetration, no such relationship can be derived for inspection with neutron sources. Instead, a unique characteristic is their high sensitivity to the presence of hydrogen, which has proven to be efficient in detection of corroded regions in structural joints [34].

As for other NDE methods, sensitivity of RT is in part dependent on the orientation of an internal material discontinuity. Using the example of a long, thin crack propagating in the through-thickness direction of a composite laminate, the most favorable orientation is such that the photon ray must penetrate the maximum distance of the crack. Hence, if a crack were arranged near perpendicular to the incident radiation, penetration through the defective media would only take place over an infinitesimally short distance. Accordingly, little attenuation, scattering or absorption would result and the recorded image would most likely reveal no sensible information. As such, sensitivity of the RT method is distinctly different from UT, where defects are best detectable at near perpendicular orientations.

6.2 INSTRUMENTATION

Mainly, instrumentation is composed of the emitting source and a suitable recording media that can be in form of a conventional film or, more recently, a digital imaging system. As discussed earlier, neutron particle machines are extremely difficult to obtain, nevertheless, their mode of operation should be discussed briefly.

6.2.1 X-RAY MACHINES

Typically, photon-emitting units are categorized by their energy level. Equipment with energies up to 125 kV is considered low energy, guns consuming between 125 to 400 kV are classified as medium energy, and all other with radiation energies above 400 kV are commonly referred to as high-energy. Up to the medium energy range, small and lightweight units are available for field inspection. Because of stray radiation, lead sheathing is normally required. Apart from safety precautions, little preparation is needed for inspection or equipment assembly. While most stationary units can be run continuously, many portable systems are operated with duty cycles, meaning they require a cool down phase in-between long exposure times [6]. Figure 6-1 shows a schematic detail of a typical x-ray tube as it is found in most conventional x-ray unit.

6.2.2 GAMMA RAY MACHINES

Exposure devices using gamma rays use isotopes that are permanently encapsulated inside a protective casing. For exposure, the radiographer cranks the source material out of its casing for a predetermined amount of time. Upon complete exposure, the source is returned into the casing for safe storage (Figure 6-2).

One significant disadvantage of γ-ray sources is their fixed energy level, whereas x-ray energy is a function of the applied voltage. Since most tubes are manufactured for operation at a certain kilo-voltage range, various thicknesses can be tested using the same x-ray unit. Also, contrast of the obtained image can be more effectively manipulated by use of x-ray units [6].

6.2.3 NEUTRON PARTICLE MACHINES

Available units for neutron radiography in the field are those comprised of accelerator guns. Such units are more restricted in terms of portability, since power and control mostly requires additional trailers or heavy equipment. Nevertheless, it offers the possibility of neutron inspection if desired as a supplementary method [34].

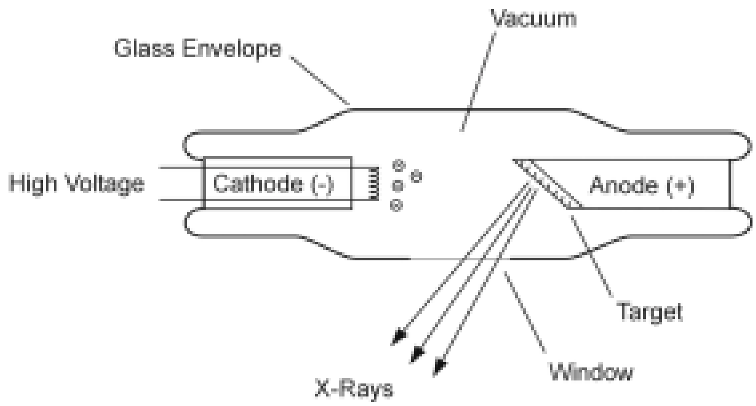


Figure 6-1: Schematic view of x-ray tube

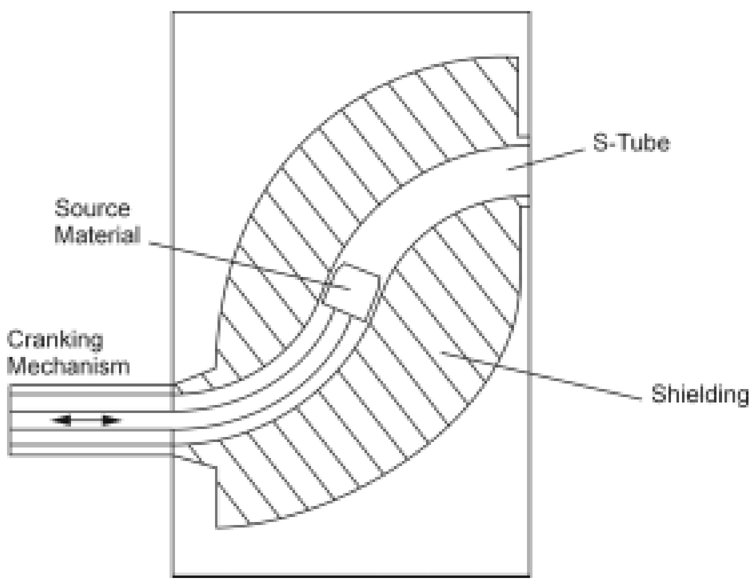


Figure 6-2: Schematic view of gamma ray machine

6.2.4 RADIOGRAPHIC FILM

To visualize attenuation and absorption of photons as they pass through the test specimen, radiographic film is still most commonly used. If properly developed, it serves as a permanent record of all discontinuities that are present along the beam path. Films consist of thin cellulose or polyester bases coated with silver halide crystals that undergo chemical changes when exposed to radiation or light. The grain size of the chemical emulsion has a significant effect on exposure rate as well as the resolution detail. Therefore, the film type must be matched with the radiation source as well as the expected minimum flaw size. Similar to photography, a radiographic film must be processed once it has been exposed. The steps involved in processing are developing, stopping, fixing, washing and drying. Visualization of the fully developed films is obtained via use of high-intensity illuminators in a preferably dark environment. Such conditions help improve contrast of the image and aids in a more detailed interpretation.

6.2.5 Real-time Imaging

Real-time imaging, also referred to as *radioscopy*, offers considerable time advantages, especially in cases where in-situ interpretation is indispensable. This method produces an instantaneous image of the radiographed section on a screen or other suitable device. It works with all form of radiation, including x-ray, γ, or neutron radiation. An important difference between conventional and real-time imaging is the fact that dynamic inspection of the object can be performed, whereas radiographic film is only capable of capturing a static image. Also, images obtained from radioscopy are displayed as positives. In contrast, radiography only allows the inspection of a negative image. Furthermore, the electronic signal obtained from radioscopy can be digitally processed to enhance image quality and eliminate noise and other unwanted information. A drawback of real-time imaging is the requirement of higher-energy sources, since a relatively short exposure time must be used to deliver successive images to the recording device [34]. This, in turn, imposes a much higher demand on safety regulations and radiation shielding.

6.3 Techniques and Applications

While conventional radiography is still commonly used for straightforward medical evaluation, other, more sophisticated techniques have found their application in the nondestructive field. This can be linked to two facts. Firstly, structural components are not susceptible to alteration of their atomic structure in such a way that long-term damage or deterioration may occur. Thus, they can be exposed to higher levels of electromagnetic energy and longer exposure times. Moreover, project specific conditions such as dimensions and geometry are highly variable whereas conditions in human radiology are mostly constant. To accommodate various material configurations, thicknesses and inspection details, a number of specialized techniques have been developed. These include methods that, unlike traditional transmission x-ray, do not require access to both sides of the specimen, as discussed in Section 6.3.1.

In recent years, RT has found a considerable interest for NDE of composites, however, it has not yet been utilized nearly as extensive as other methods. The main reason might be high safety regulations and cost that are significant drawbacks of the technique. Nevertheless, several promising projects have utilized RT, indicating a high potential of this method, especially for inspections where high detail of thick members is desired.

6.3.1 Compton Backscatter

This specific application of radiography utilizes a portion of the attenuated radiation as it passes through a material. As mentioned earlier, radiation can be attenuated by absorption or scattering. Latter can occur in form of *Compton scattering*, a process where photons in the 0.1-3.0 MV-range interact with orbital electrons of the test material. This interaction causes photons to be reflected into different directions with a usually lower wavelength [6].

One highly useful application of Compton backscattering is the inspection of multiple delaminations in impact-damaged composite laminates [35]. The technique is especially suitable for this form of defect since it is capable of visualizing defects at multiple depths. Also, delaminations oriented parallel to the laminate can be identified. Unlike transmission x-ray, Compton backscatter detects a variation of material density in terms of scattering characteristics. Hence, thin delaminations can be sensed. This was shown on 2.3 mm-thin carbon-epoxy laminates using a 100 kV x-ray tube with scanning resolution of 0.02 mm [33]. Despite this excellent resolution, Compton scans are susceptible to contamination and blur from a number of sources. These include voltage fluctuations, scanning fixture vibrations, and irregularities in fiber/matrix distribution. Latter indicates the extreme sensitivity to signal noise if Compton backscattering is applied to material that do generally not possess a high material uniformity, as may be expected in externally bonded laminates manufactured by the wet lay-up process.

6.3.2 Computed Tomography

Through digitization of radiographic images at a large number of varying angles, 3-dimensional representation of the test object can be produced. One such method that is commonly used in medical evaluation is computed tomography (CT). In this method, where access to both sides of the specimen is required, the part under inspection is places between the source and recording device while being rotated about different axes. Individual images are stored in a computer and reconstructed to form a 3-dimensional image [34]. Recently, engineering applications of CT have increased substantially, as described in [36] and [37].

In general, CT is a volumetric method, i.e. any feature to be detected must have adequate volume. Consequently, disbonds that are in intimate contact cannot be sensed using this technique. Reference [37] discusses the use of CT for detection of common material flaws in adhesive bonds of a T-spar to panel section in an aerospace application. Further, results found were compared to those from conventional UT data. Although both methods were capable of indicating the defective regions in size and location, UT could not provide cross-sectional information on the cause. Tests on other specimens proved high applicability of CT to detection of resin-rich and resin-starved areas as well as fiber misalignment. Nonetheless, it must be emphasized that cost of this method is significantly higher than that of other methods. CT should therefore be preferred in manufacturing control rather than for in-situ testing.

6.4 Safety Considerations

An important aspect of radiation is that, as materials are penetrated, it ionizes matter by knocking electrons out of their orbit, thereby changing their electrical balance. Unless adequate precautions are taken to block radiation, such ionization eventually causes alterations in the human tissue. Furthermore, lack of human perceptibility to these forms of radiation makes RT extremely dangerous when operated in-situ, particularly if done so by inexperienced personnel. Damage to human cells is mainly dependent on the amount of radiation that has been absorbed during exposure. The three essential safety parameters in radiographic testing are time, distance, and shielding. Generally, shorter exposure times are most favorable. Also, far distances to the area of testing are preferable, since exposure decreases with distance by an inverse-square relationship. Lastly, shielding through use of lead protectors can block most of the electromagnetic radiation. One should be aware of these indispensable safety precautions before considering radiographic inspection as a potential in-situ NDE method.

6.5 Capabilities and Limitations

One of the most outstanding advantages of radiographic testing is the extreme accuracy and sensitivity that can be obtained. Most types of defects can be detected, including porosity and matrix cracks. Further, no surface contact is required, hence almost any geometric configuration can be inspected. This also holds true for maximum thickness, where RT allows for a broad range that encompasses both thin membranes as well as solid concrete members. Since radiographic imaging has been used for many decades, equipment is readily available and most of the capabilities and limitations are well understood.

In an adequate laboratory environment, most of the safety hazards related to radiography can be eliminated, leaving little chance for damage to humans. Also, the energy levels required for operating RT equipment are more readily available in stationary testing. In contrast, in-situ inspection requires a mobile energy resource to be situated in the field, while the largely uncontrollable environmental factors and variable site conditions tend to impose significantly higher risks of operation. The safety precautions stringent to RT typically come at a higher cost and can disqualify the technique based on unjustifiably high expenses, which may further go to the expense of flexibility and rapidness of an in-situ method. Summarized, safety and energy supply remain as two of the main drawbacks that must be taken into consideration, as they are important factors for both contractors and inspectors.

Nevertheless, if these factors can be controlled, the excellent sensitivity and resolvability of RT imaging can result in a highly transparent inspection of solid components and possibly provide the most comprehensive information among all formerly discussed NDT techniques. Undoubtedly, the method provides the most exhaustive information on defects of extremely small size, which makes it preferable for certain well-controllable inspection environments.

7 THERMOGRAPHIC TESTING

7.1 Fundamentals and Theory

In a general sense, thermography entails measurement and graphing of isothermal contours on the surface of an object [38], in that it displays the effects of temperature differences in materials caused by presence of internal discontinuities. In theory, all heat transfer within a material as well as transfer from one material to another is related to conversion of heat energy. Herein, different methods of thermography are used, which can be classified as either *passive* or *active*. The passive form of thermography monitors anomalies in temperature profiles of a part under normal environmental or operating conditions. Examples of passive inspection are thermographs of a roof structure or operating machinery, since both components store internal energy and are thus capable of radiating thermal signals without the need for external excitation. Former examples differ insofar that structural components obtain energy predominantly from ambient sources, such as the sun, whereas operating machinery develop heat by means of internal friction. Because a quantitative assessment on the heat emitted from these sources is oftentimes not possible, passive thermography is mostly qualitative in that is used to simply pinpoint anomalies [39]. In contrast, active thermography uses external heat sources to induce energy to the specimen and thereby characterize defects on a more qualitative basis. For a majority of sources, duration, magnitude and frequency of the electromagnetic wave are known entities that can be controlled and adjusted by the user. Lately, a variety of techniques have become available for active thermography, which will be discussed Sections 7.3.1 through 7.3.3.

7.1.1 Forms of Energy Transfer

Heat can be transferred by one of three modes: *conduction*, *convection*, and *radiation*. Which mode is predominant mainly depends on the media in which the energy transfer is taking place. As such, transfer in solids is primarily occurring in form of conduction, where two adjacent molecules transfer thermal energy between themselves. Fourier's law describes how much heat is transferred and is expressed by:

$$Q = \frac{k}{t \cdot A \cdot \Delta T} \qquad (5)$$

In the above equation, *k* describes a material's *thermal conductivity*. Materials with a high *k*-value, such as metals, are efficient conductors of heat energy, i.e. heat flow through the material occurs fairly rapidly. Composites, in contrast, are relatively poor conductors. This property comes as an advantage to thermographic inspection, since differences in the heat pattern, which are representative for anomalies, approach thermal equilibrium at a relatively slow rate. Hence, discontinuities can be distinguished over a longer period, leaving more time for inspection and data acquisition. Furthermore, a higher contrast can be obtained in materials of higher thickness.

Convection primarily occurs by subsequent mixing of molecules and is thus mainly present by interaction between liquids or gases. This is important in thermographic imaging, since water or wind forces acting on a surface can significantly affect its temperature.

Radiation is inherently different from both previous forms of energy transfer in than it is a form of electromagnetic radiation. So-called *infrared* radiation (IR) possesses certain characteristics that are similar to those of light or x-rays, although it is of significantly lower frequency and hence longer wavelength. As indicated in Figure 1-4, the spectrum of infrared radiation ranges from roughly 10^{-4} to 1 cm in wavelength. Hence, IR is comprised of waves exhibiting much lower energy compared to x- or gamma radiation, which allows application with virtually no safety restrictions. In addition, IR-sources required for development of infrared radiation show a much lower energy demand. While x-ray equipment is operated in the kV range, IR-radiation can be generated from only a few volts.
Similar to conduction, radiation is governed by a thermodynamic relationship, given as

$$Q = \sigma \cdot \varepsilon \cdot T^4 \qquad (6)$$

Radiation, governed largely by its material specific parameter ε, denoted as *emissivity*, may be viewed as one of the main parameters in thermographic imaging. When electromagnetic radiation is given off by an external heat source and allowed to interact with a surface, it can be reflected, transmitted or absorbed. Here, the corresponding parameters are denoted as *R'*, *T'* and *A'*, respectively. Due to conservation of energy, the total energy present can be divided into these three components

$$R' + T' + A' = 1 \qquad (7)$$

with their sum being equal to 100%. Since most materials that are inspected via IR are opaque, the transmitted part can be omitted from the equation, leaving only those fractions that are either reflected or absorbed. If *R'* = 1, the surface reflects all the energy, almost acting like a heat mirror, and no assessments about the internal material properties can be made. Although no such material exists, most metals are approaching a value of 1. On the other hand, emissive objects with $A' \cong 1$ reveal most about their internal temperature composition. For most nonmetals, such as composite materials, emissivity lies in the range between 0.8-1 (it can reach values as high as 0.98 for pure graphite [39]) indicating their suitability for thermographic inspection. Generally, it is not recommended to make IR measurements on materials with emissivities below 50% [6]. One must further be aware of the fact that emissivity of a material can be affected by various environmental factors. As such, surface condition, temperature and angle of view are parameters that must be monitored carefully to ensure consistency of results [6], [39].

7.1.2 IR TRANSMISSION

To allow monitoring of the emitted IR radiation, it must be effectively transmitted from the test surface to the detecting unit. In most applications, radiation must pass through the atmosphere, which happens to be fairly transparent to IR radiation. The simple fact that a media is transparent to light does not indicate that the same holds true for IR. In fact, heat radiation is most effectively transmitted in one of two wavebands, 2-6 μm and 8-14 μm. In-between former ranges, air allows only limited transmission of infrared radiation. Since recording devices are typically in form of a camera, lens material as well as CCD devices have to be matched such that they allows transmission/reception of thermal radiation.

7.1.3 Defect Detection

Although CFRP materials consist of two distinctly different phases, a properly laminated composite material will have relatively uniform thermal characteristics. Once a disbond, delamination or other anomaly has been introduced, the thermal pattern within the composite will be altered. As for other NDE methods, the sensitivity of thermographic inspection has its limitations when it comes to type and size of a defect in particular. Because different materials possess different values of thermal conductivity, regions such as disbonds or air inclusions tend to build up heat, thus indicating the location and size of the flaw. Figure 7-1 shows a comparison between thermal patterns in steel and composite materials. Assuming equal magnitude and duration of the heat imposed onto both samples, the composite sample will conduct heat at a slower rate, i.e. thermal energy does not spread as rapidly throughout the part as it would in the case of a steel sample of comparable dimensions. Also, as may be seen, heat propagation will occur more rapidly along the fiber direction. The significantly higher conductivity of carbon facilitates more rapid heat propagation compared to the transverse direction.

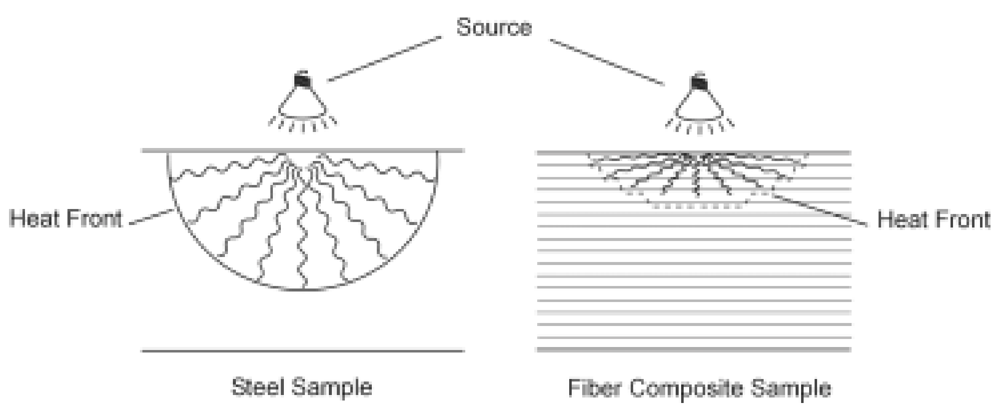


Figure 7-1: Thermal conduction in steel (a) and composite samples (b)

7.2 Instrumentation

A complete thermographic imaging system for active thermographic inspection is typically comprised of a thermal stimulation system (air guns, heat lamps, etc.), an IR camera and an image and analysis system (display, TV, etc.). In passive thermography, however, ambient or internal heat sources substitute use of an external heating device.

7.2.1 Stimulation Devices

Thermal perturbations can be deployed in two forms, either by cooling the specimen or by heating it. Which device is given preference is mainly depending on the specific application as well as the material’s thermal properties. Examples of cooling devices are liquid nitrogen spray or cool water jets. High-powered lamps, photographic flashes, laser beams or heat guns/air jets, typically perform external heating. The main desirable characteristics of these devices are consistency and reproducibility. These parameters are important to conduct continuously representative tests over longer time periods without experiencing loss in heat energy that might yield different results. Herein, the level of automation is of extreme importance, as non-uniform heating will lead to heat buildup, which may later be interpreted as an imbedded material flaw. Consequently, heat intensity, distance to the source, exposure time as well as the heating/inspection intervals must be held consistent. While this is most successfully done using a fully automated system, manual heating assemblies can also make use of features that ensure a more uniform and reproducible introduction of heat into the part. One such example are semi-automated heating tools as shown in Figure 7-2. Although manually operated, an integrated driving mechanism allows movement over the part surface at near-constant velocity and distance. By altering wheel diameter and velocity, this tool can adjust to a range of material- and test conditions.

Figure 7-2: Semi-automated heating device

Depending on emissivity of the material under investigation, duration of the heat (or cooling) pulse must be adjusted. As such, materials with high emissivity generally require longer exposure times compared to materials that show high conductivity/low emissivity. A calibration procedure might be required to adjust impulse duration to obtain most insight to material properties.

7.2.2 IR CAMERAS

The primary function of IR cameras is the conversion of radiant infrared energy into a detectable electric signal. An essential parameter is described by the minimum measurable temperature difference, which is directly related to the sensitivity of the detection device. Most modern cameras are capable of detecting temperature differences as small as 0.1°K (0.18°F) [10]. On more advanced units, temperature gradients in the milli-kelvin range can be discriminated. Many of the modern devices are similar to conventional CCD chips since they form video images directly from on-chip electronics. Resolution is fairly high and is typically in the range of 752×582 pixels. To capture rapid changes in surface radiation to a sufficient detail, cameras are commonly operated at a minimum of 30 frames per second. For special applications, where short heat pulses are used for external heating, frame rates of up to 60 frames per second or more might be preferred. Cooling mechanisms are often used on these cameras to enhance detectivity by reducing ambient electromagnetic noise to an acceptable level. This can be performed by use of *cryogenics* or through thermoelectric elements, which cool down when an electric current is applied to two dissimilar metals. The cost for portable infrared cameras typically ranges from $25,000 to $70,000, depending on sensitivity and resolution of the CCD unit.

Users should be aware of the fact that lenses for IR cameras are substantially different from those used for conventional video recording. Whereas conventional lenses are transparent to visible light, IR lenses are manufactured from germanium, silicone or zinc selenide, which are opaque to visible light. However, these materials are highly effective in transmitting infrared radiation, as discussed in Section 7.1.2. As shown in Figure 7-3, the overall dimensions of IR cameras are mostly comparable to those of conventional video camcorders, which makes them highly preferable for environments that require high mobility and flexibility.

Figure 7-3: IR camera

7.2.3 Analysis Systems

As most IR cameras are not equipped with integral imaging systems, image display and data analysis must be performed utilizing a remote system. Such remote analysis systems are comprised of an electronic unit that converts the electric signals of the IR cameras into a thermal image. A number of controls are available to adjust for thermal level, range, emissivity and other parameters [6]. The processed data is most conveniently imaged on a liquid crystal display (LCD) in either grayscale or color to allow rapid visualization of critical areas and to further identify those that may require a more detailed inspection. While grayscale provides sufficient detail, color imaging should be preferred for in-situ applications where difficult lighting conditions may otherwise hinder correct interpretation. A number of different color palettes can be selected to display various radiometric parameters. Typically, the display selects a series of distinct colors, each covering a specific window or range of the total frequency band. Use of computer programs further enables the user to perform a number of on-screen modifications and allows export of data into spreadsheets for further analysis. Examples of a typical computer analysis system as well as a hand-held LCD unit are shown in Figure 7-4 and Figure 7-5, respectively.

Figure 7-4: Portable IR analysis system

Figure 7-5: Hand-held LCD screen

7.3 TECHNIQUES AND APPLICATIONS

Due to the advantageous thermal properties of composite materials, thermographic NDT has found extensive use over the past decades [10], [40], [11], [41]. As for ultrasonics, a variety of thermographic methods have been developed to suit individual material- and geometric configurations. As discussed earlier, thermal testing can be performed either passive or active, depending on availability of an ambient source and overall dimensions of the structure to be inspected. In most cases, passive thermographic testing is given preference on large projects, such as detection of heat-loss in sections of an entire building [42]. While passive testing of large areas can provide insight on variations in thermal diffusivity, results are mostly qualitative and relevant only for evaluation on a structural level. For quantitative inspection, i.e. detection and characterization of defects, an alternate methodology must be followed. If magnitude and duration of individual heat pulses are known, a more exact study on internal properties can be pursued. Hence, active methods are generally preferred for NDE of composites, as duration and energy of the heat pulse are more easily adjustable. In the following, some of the most frequently applied methods are reviewed and discussed.

7.3.1 Pulsed Thermography

Pulsed thermography can be considered the foremost thermal stimulation technique [39]. Herein, a heat pulse of relatively short duration, exerted from a conventional lamp, heat gun, strobe light or laser beam, is directed at the test surface (Figure 7-6), causing a thermal front to propagate into the material by means of diffusion. The corresponding thermal image of this process is depicted in Figure 7-7. As may be noted, heat generated by the strobe light appears in white, indicating a high level of intensity.

Figure 7-6: Thermal stimulation using a hand-held source

Upon completion of the thermal stimulation, a temperature decay curve of the specimen surface is continuously monitored and recorded by one or multiple external recording devices. Presence of any subsurface anomalies will alter the rate of diffusion with respect to the surrounding area. As such, entrapped pockets of air tend to retain heat longer and serve as so-called *hot spots.* This phenomenon is mainly due to the low thermal conductivity of air as well as the comparatively high heat flow rate in the surrounding material. As discussed in Section 7.1.3, areas of low thermal conductivity will inhibit rapid heat flow through the material and thus restrict loss of thermal energy during the cooling cycle. An example of such thermal energy buildup in a filament-wound CFRP shell is illustrated in Figure 7-8. During specific instances of the cooling cycle, both helical and localized regions of higher intensity could be identified, serving as possible indicators for resin buildup in regions of tape overlap and air entrapment in-between winding cycles performed at various orientations.

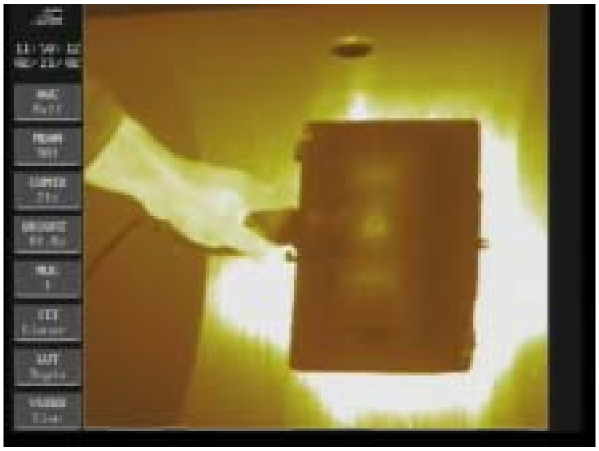


Figure 7-7: IR image of thermal stimulation

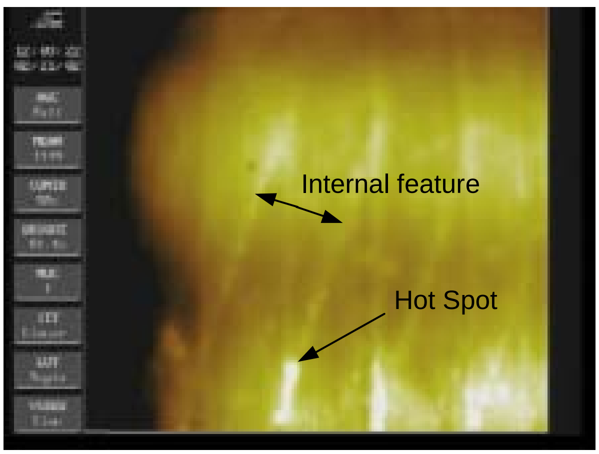


Figure 7-8: IR image of thermal gradient caused by internal anomalies

Although differences in thermal conductivity apply to composite materials and metals alike, the low emissivity of latter often restricts imaging of thermographic contours altogether (Section 7.1.1). Due to the rapid flow of thermal energy through metallic bodies, duration of the heat pulse is mainly governed by the conductivity of the material. Herein, metals require only short pulses of a few milliseconds whereas composites may necessitate exposure times of up to several seconds. If long exposure times were to be used on metals, the rapid propagation of thermal energy would overwhelm most of the information given off by localized internal anomalies. For anisotropic materials and laminated composites in particular, it should further be noted that conductivity varies significantly among the various configurations, mainly depending on the specific fiber type, layup sequence as well as fiber-, resin-, and air contents. As such, glass fiber reinforced polymer (GFRP) composites generally show a low conductivity, whereas certain graphite fibers can have conductivity comparable to metals, as may be seen in Table 2. Hence, to capture the temperature decay of CFRP to the desired detail, higher frame rates may be required

Alternative to monitoring the temperature decay curve on the heated side of a component, one may chose to allow transmission of heat through a part and capture the heat signature on the far surface. In this arrangement, heat flow through a part will be restricted in regions of low *k*-values (voids, porosity, volatiles or water), resulting in a region of lower temperature to be noted in the heat-contour image. Since this arrangement requires access to both sides of a part, applicability of through transmission is mainly restricted to parts of minimal thickness. On structural components, through transmission would typically require dismantling or may not be possible at all. The general test setup employed in both test arrangements along with a characteristic image obtained from each test setup are shown in Figure 7-9.

Table 2: Thermal conductivity of various materials

SUBSTANCE	THERMAL CONDUCTIVITY, *k* [W/m-°C]
Carbon Fibers (longitudinal)	84
Carbon Fibers (transverse)	0.84
Epoxy Resin	0.18
CFRP (transverse, V_f = 65%)	0.72
Steel (20°C)	36-54[†]
Concrete (20°C)	1.37

[†] depending on carbon-content

The use of pulsed thermography for inspection of CFRP materials has been well documented in the literature, including studies by Hawkins, Jones and Berger, and Maldague [11], [40], and [43].
Hawkins investigated the detectability of debonds on composite overwraps for circular concrete columns in an in-situ environment. In this study, the heat source consisted of 12 quartz lamps, having 500 watt/lamp, mounted on a semicircular frame. A distance of 100 mm to the test surface was kept constant while the fixture was descended from the top of the column at a speed of about 70 mm/sec. Roughly 15 seconds after heating, IR images were captured. In order to ensure a damage-free inspection process, surface temperature of the composite never exceeded 40°C. It was shown that debonded regions in form of entrapped air pockets of about 100 mm in diameter could be identified using this method.
Reports on impact damage have shown that IR imaging is an effective tool for detection of barely visible impact damage [40]. The inspection was carried out on 0.25 in thick CFRP samples that had suffered a range of impact delamination. Tests were conducted using a quartz halogen lamp as the heat source and a camera in the 8-11 μm wavelength band as the receiving unit. Inspection in both transmission and one-sided modes showed

a large effect of test mode on thermal contrast, and thus, detectability of damage. As such, increasing depth and decreasing flaw size yielded decay in detectability for the one-sided inspection mode. For small flaws, the contrast approached zero, even at shallower depths. A comparison of this method to ultrasonic inspection and eddy current testing (to be discussed in Chapter 8), showed that IR pulse inspection was capable of revealing impact damage to a degree equivalent to that obtained from other methods.
The main advantages of pulsed IR testing are the ease of deployment for in-situ inspection and the relatively short inspection time due to surface-wide heating and monitoring [43]. Difficulties may arise in computation of thermal contrast for which temperature differences between good and defective regions must be obtained. This, however, demands *a priori* knowledge on which areas are defect free [39].

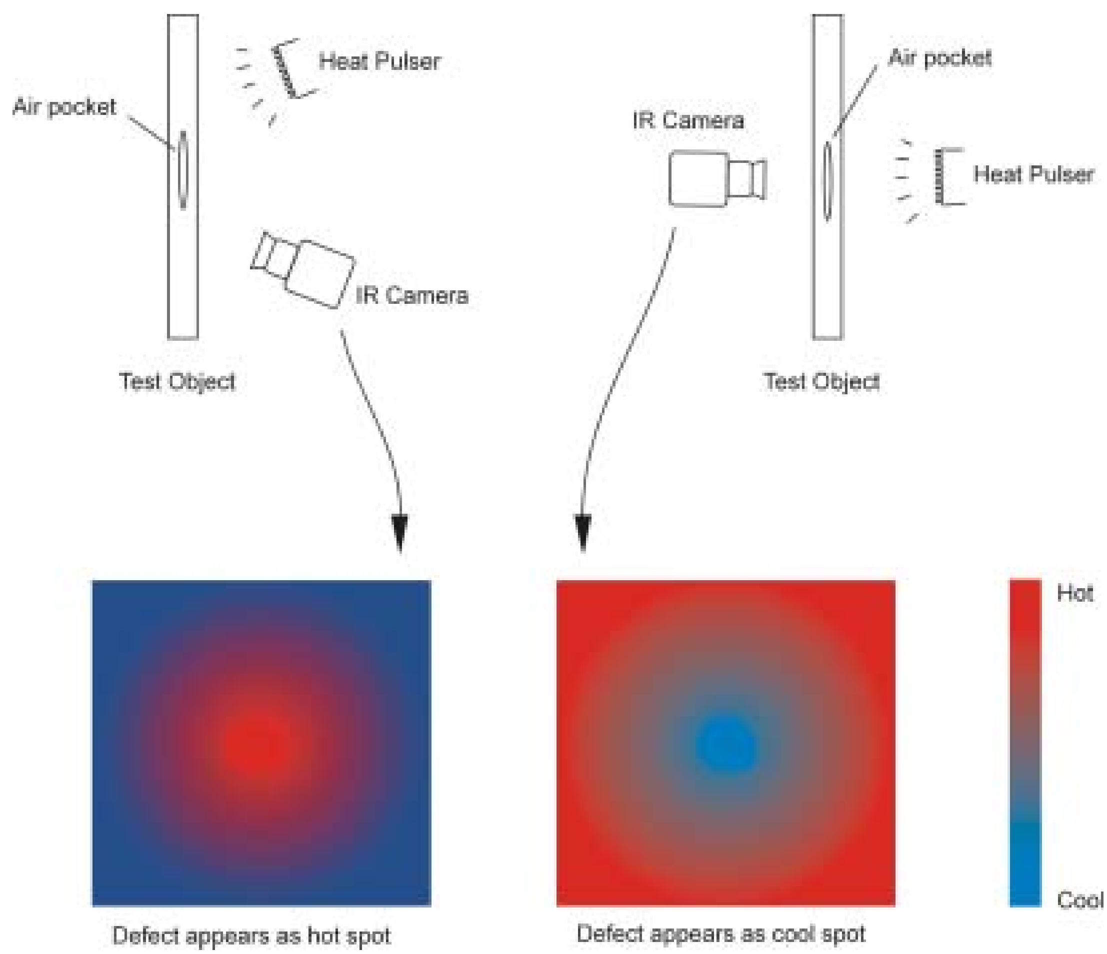


Figure 7-9: Qualitative representation of one-sided (left) and through-transmission IR testing (right)

7.3.2 Lock-in Thermography

Modulated infrared thermography, commonly referred to as *lock-in thermography*, is increasingly being used for evaluation of CFRP materials. Lock-in refers to the need for synchronization of both input (modulated heating) and recorded signal. The technique is generally based on the submission of specimens to sinusoidal temperature stimulation (Figure 7-10). Such stimulation causes an oscillating temperature field inside the specimen, which can be recorded remotely through IR capturing devices. Sine-modulated external heating can be performed using a laser source such that both amplitude and phase of the signal become available. Since both parameters differ between good and defective regions of the laminate, conclusions on internal discontinuities can be drawn [44].

In addition to the standard IR testing equipment, lock-in thermography requires use of a lock-in module that drives the heat source and is controlled by a system controller. During inspection, IR recording of the oscillating surface temperature is synchronized with the modulation frequency and multiple images are taken per modulation cycle. These signal values are captured in the lock-in system and used to calculate the phase difference between object and heat source.

Successful application of this technique is reported by Bai and Wong [44]. They inspected specimens with 30 layers of CFRP lamina (totaling approximately 4.2 mm in thickness), containing various artificially implanted layers of Teflon film. Defect size ranged from 1 to 11 mm in diameter at depths between 0.28 and 2.8 mm. Both, heat source and IR camera were positioned on identical sides of the specimens at a distance of 0.5 and 0.6 m, respectively. The heat modulation frequency was varied over a predefined range to evaluate its effect on defect detectability. It was found that, depending on defect size and depth, a “blind frequency” exists at which no distinct phase difference is apparent. Contrary, optimum frequencies exist that are most suitable for displaying defects or certain size and depth. While large defects could be detected throughout the entire depth range, phase differences of defects ranging from 1 to 6 mm in diameter were not sufficient for detection. However, because differences between thermal properties of Teflon and CFRP are less pronounced than between air and CFRP, the detectivity of this specific application can be considered as conservative.

Summarized, lock-in thermography is capable of performing inspection of near surface defects in composite laminates to a satisfactory degree.

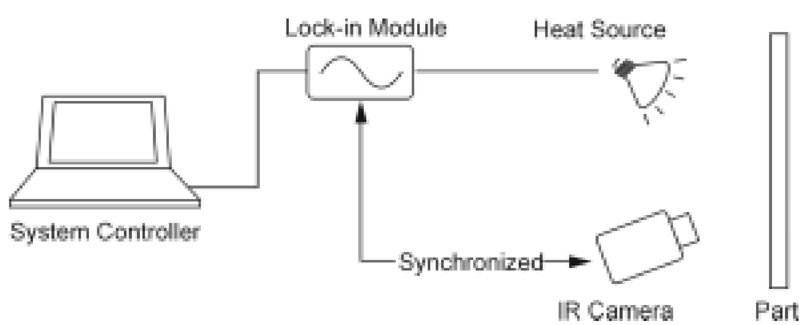


Figure 7-10: Modulated heating in lock-in thermography

7.3.3 VIBROTHERMOGRAPHY

Instead of using an external heat source, vibrothermographic imaging uses the effect of externally induced mechanical vibrations to release heat energy inside the test object, as shown in Figure 7-11. Even in the elastic range, heat is emitted by dissipation of mechanical energy through nonconservative micromechanical deformation processes such as dislocation motion, impurity diffusion, and other complex atomic activity [38]. For polymeric composite materials, it has been shown that viscoelastic dissipative hysteresis dominates heat generation [45]. It may be assumed that these dissipative mechanisms remain below a level that would be considered destructive testing of the material. When excited, the presence of stress concentrations at flawed regions in the material will cause disturbance in the vibration mode shapes and thus be observable in the heat pattern. Using conventional real-time IR imaging, thermal gradients on the part surface can be recorded and interpreted.

The most important parameters in vibrothermography are amplitude and frequency of the mechanical excitation. To fulfill the definition of nondestructive testing, the amplitude of stress/strain levels must be limited to roughly one third of that equivalent to failure of the material under inspection. For most situations, such amplitude levels are sufficient to produce observable heat patterns [38]. A trial and error procedure is often followed to determine the frequency at which thermal patterns develop. Since most of the energy-dissipating mechanisms are frequency dependent, a steady increase of frequency throughout the predetermined frequency band is practiced. The typical excitation frequencies range from 0 to 25 kHz, while most heat patterns in composite materials are created in the range between 5 to 30 kHz. It was found that formation of thermal patterns is highly sensitive to the applied frequency. As such, variations of ±0.5 kHz from the resonant frequency can cause thermal gradients to appear or vanish [38]. Hence, a gradual increase in excitation frequency over the entire frequency band is essential in finding the most suitable test condition.

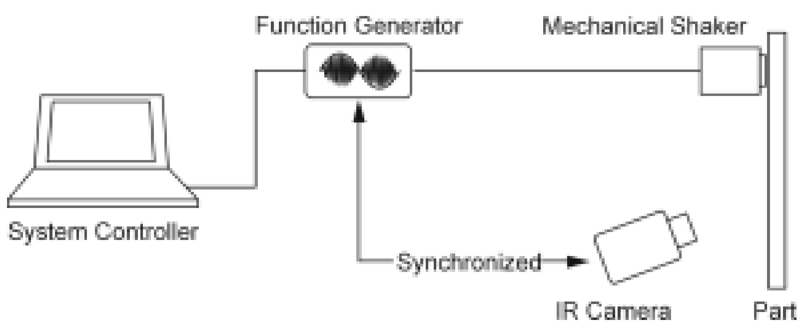


Figure 7-11: Vibrothermographic testing

Apart from the equipment listed in Section 7.2, vibrothermographic testing requires utilization of mechanical shakers. For high frequency excitation, electromagnetic coils or piezoelectric transducers are commonly used. Further, a suitable couplant is required to efficiently transfer mechanical energy from the excitation device to the part surface.

Reports on experimental evaluation of vibrothermography for detecting delamination in CFRP strips are given by Rantala et al. [46]. Instead of using constant excitation amplitude, lock-in amplitude modulation, as discussed in Section 7.3.2, was utilized. To generate sufficient hysteresis energy per time while ensuring purely non-destructive test conditions, high excitation frequencies were chosen. This enabled the examiner to keep the amplitude below the critical level or one-third the failure stress, as mentioned earlier. In contrast, improved depth range was obtained via use of low-frequency amplitude modulation.

Unlike lock-in- or pulsed thermography, vibrothermographic inspection provides more insight into the mechanical state of the material, because thermal patterns are directly related to mechanical stress, while those of techniques discussed in Sections 7.3.1 and 7.3.2 are based on differences in thermal conductivity. Compared to other IR techniques, vibrothermography can detect defects such as closed cracks or delaminated regions (cold bonds), which are not detectable by pulsed IR or lock-in thermography. Also, the method has proven to be highly suitable for in-situ inspection provided that the mechanical excitation can be achieved.

7.4 CAPABILITIES AND LIMITATIONS

Independent of its specific form, thermographic imaging has significant advantages over many other NDE techniques, primarily due to fact that it provides a quick and more comprehensive insight to material properties. Due to the capability of covering large areas at relatively short duration, thermography can be applied in both near- and full-field. The high sensitivity of modern recording equipment (±0.1°K temperature difference) provides spatial resolution with such detail that thermal imaging is often prioritized over visual inspection [6]. An example of the extremely high sensitivity of modern IR cameras may be seen in Figure 7-12, showing the heat gradient induced from a human fingerprint on the surface of a CFRP shell structure. Duration of heat introduction was only about one second.

Figure 7-12: Fingerprint on a CFRP shell

Being a non-contact technique, it allows inspection of highly complex geometric configurations. The high portability of a complete thermographic system of less than 2.5 kg (~5 lb.) gives further support to thermography as a suitable field inspection method.

Although difficulties can arise using reflective or highly conductive materials, composites are nearly ideal for thermographic imaging. Their high coefficient of emission of about 1, in combination with typically low values of thermal conductivity allows high contrast imaging of thermal gradients. Also, in vibrothermographic examination, their high loss angle (or damping of elastic waves) provides an efficient conversion from mechanical to thermal energy [46].

Nevertheless, thermography has its limitations with respect to depth range and defect characterization. Since only the surface of an object can be viewed thermally, internal defects must be of sufficient magnitude to affect heat transfer at the surface. As discussed previously, small defects at considerable depth can rarely be identified. Moreover, assessment on defect type depends largely on experience of the inspector, because thermal patterns simply reveal regions of stress concentrations, which can originate from a variety of different defects, such as porosity, voids, fiber breakage, etc.

Under field conditions, a number of environmental effects may further complicate inspection with infrared sensors. Because all thermal mapping is dependent on fluctuation in surface heat patterns, any rapid variation in ambient temperature may restrict the use of thermographic imaging. Factors like rapid changes in sun intensity, precipitation or wind can possibly influence heat patterns to a degree that will result in erroneous IR readings. Thus, to provide stable test conditions, adequate protection from random ambient radiation must be provided at all times during testing.

8 EDDY CURRENT TESTING

8.1 FUNDAMENTALS AND THEORY

Due to their non-magnetic nature, composite materials are largely unsuitable for magnetic inspection techniques. Specifically, use of magnetic particles, a method that finds extensive use in NDE of metallic substances, cannot be applied to composites. Nevertheless, carbon-epoxy composite materials are suitable for inspection via electromagnetic induction, since carbon allows for transport of electrons among atoms. Although the material itself cannot be magnetized, it is amenable for magnetic lines emitted from electromagnetic coils or other similar induction devices.

The inductive nature of carbon fibers has been utilized for NDE of composites by development of the eddy current testing (ET) method. Eddy currents are produced when a coil circuit, driven by an alternating electrical current, is brought in close proximity to the test specimen. The alternating magnetic field that is caused by the driving coil induces a voltage into the test specimen. As a result, electrons in the material under investigation are forced to circulate in an eddy-like pattern, while the circular currents themselves form a magnetic flux field that can be picked up by either the driving coil or a second, separately placed coil (Figure 8-1). Alterations in current flow through the pickup coil can then be related to a number of material anomalies [6]. While induction of magnetic flux does not require contact between the coil and test material, induction is highly sensitive to lift-off (spacing between sample and coil) and the angle between the induction coil and the test surface [47].

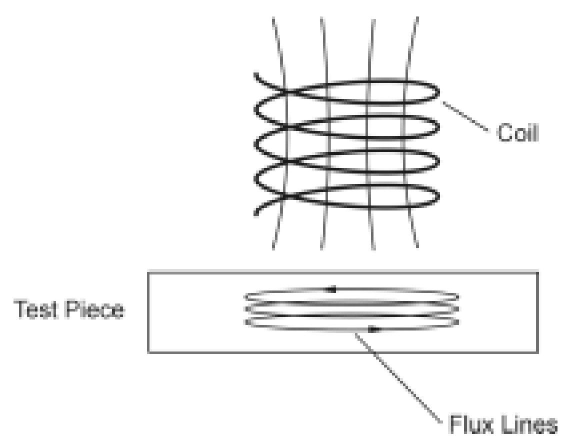


Figure 8-1: Induction of electromagnetic flux

Performance of the ET method greatly relies on the electrical conductivity of the test material. Conductivity describes the ability of the material's atoms to conduct electricity, whereas resistivity, the opposite of conductivity, yields its ability to resist electric flow. How well a material conducts is solely governed by the number of electrons present in the outer shell of the atom. Materials with a high number of outer-shell electrons, such as seven or eight, are *insulators* and cannot develop electric flux. For carbon, two electrons are present in the outer shell, which classifies it as a *conductor*. Any material of such atomic composition is capable of transporting electrons among its atoms. While electrical conductivity can be assumed as a constant value depending on the specific material composition, it can be influenced by variations in temperature as well as frequency of the driving coil [6].

Unless the test material is interspersed with boundaries or discontinuities, eddy currents flow in circular patterns. Upon encountering a material anomaly, eddy current flow is likely to be altered, which corresponds to a change in current flow in the pickup coil. Although a number of material defects can be detected using eddy currents, size and orientation of defects are the governing factors for detectability. In order to be noticed, the defect must be of considerable size such that it can cause a detectable change in the current flowing through the pickup coil. Since flux lines travel in circular paths, defects orientated tangential to the line pattern are more difficult to detect than those that are located perpendicular, as depicted in Figure 8-2.

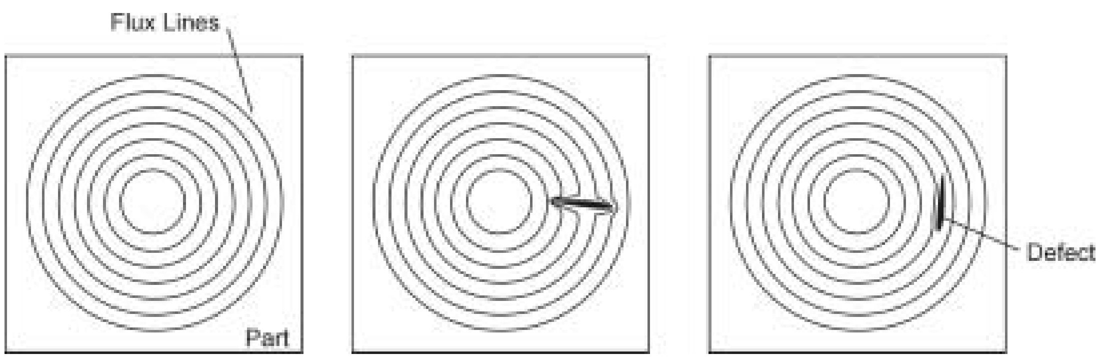


Figure 8-2: Flux patterns near material anomalies

Similar to other NDE methods, ET entails specific performance criteria that define its suitability for non-destructive evaluation purposes. These include sensitivity, penetration and resolution. While highest sensitivity in near surface regions can be achieved in materials with high electrical conductivity, penetration decays rapidly with increasing depth. This is due to secondary flux, in which the flux lines developed in the test material cause cancellation of primary flux induced via the driving coil. Due to a low resistivity (i.e. high conductivity), this phenomenon is particularly pronounced in most metallic substances, such as iron and steel.

Since the driving coil utilizes an alternating current to induce the magnetic flux, its driving frequency can be adjusted to obtain best results. Commonly, frequency ranges between 50 Hz and 10 MHz are used [6]. As in ultrasonic testing, an increase in frequency results in increased sensitivity to small discontinuities, while penetration into the material is significantly reduced. As a rule of thumb, coil diameter defines the maximum penetration depth while it also governs the minimum equivalent defect size detectable [6].

In CRFP materials, fibers are the only conductive component. Hence, only defects that are directly related to damage or disorientation of fibers can be sensed by this method. Depending on the specific type of CFRP, its electrical resistivity can vary between 3,300 to 10,000 μΩ-cm in direction parallel to the fibers and 140,000 to 50,000,000 μΩ-cm in the transverse direction [47]. This implies a much higher penetration depth for CFRP as compared to most metals, which have resistivity values that range from 16 to 60 μΩ-cm [6]. However, it requires much higher excitation frequencies to provide sufficient interaction between the eddy fields and the material. As a result, special coil arrangements may often be required.

8.2 INSTRUMENTATION

Test equipment for eddy current testing is generally comprised of an alternating current (AC) generator and processing unit as well as a coil of variable size and arrangement. Modern instruments are compact in size and light enough so they can be easily transported.

8.2.1 AC GENERATORS AND PROCESSING CIRCUITRY

The generator of most standard units drives the coil at only one frequency, which necessitates that the unit is matched to the specific application in terms of material type, dimensions and flaw to be detected. Common adjustments that can be made on standard unit include frequency, gain (amplification of output signal), gates, filters, etc. A high-resolution display can be used to display important information simultaneous and convenient for the operator.

A significant advance of ET has been the introduction of multi-frequency units. Due to the fact that pickup coils are sensitive to a multitude of frequencies, signals from more than one source often combine to form a signal that becomes difficult to interpret. By using more than one frequency at a time, undesirable frequencies can be filtered out. Examples for this are inspection of non-metallic materials that are in close contact to a metallic surface. Such material combination often results in erroneous interpretation if using single frequency instruments. Other aspects of multi-frequency instruments include reduction of inspection time by simultaneous operation in two or more inspection modes as well as near surface inspection at high frequency while penetrating deeper into the material by using a second, lower frequency [6].

8.2.2 COILS

Coils resemble an important element of the eddy current system since their size and arrangement is predominant in fitting the test object. While large coils provide means for scanning large areas at one time, they sacrifice sensitivity to small defects and are often unable to pinpoint local material deficiencies. Conversely, use of extremely small probes can result in a tedious and time-consuming inspection process.

The three main categories of coils are surface coils, encircling coils and internal coils. Only the former type will be addressed in this discussion, as encircling and internal coils are not suitable for external inspection of structural components.

8.2.2.1 Bobbin Wound Probes

A majority of coils used for surface inspection are made of wire wound around a hollow core and are commonly referred to as 'bobbin wound'. They are designed to be held perpendicular to the test surface and are highly sensitive to surface cracks and discontinuities that are oriented perpendicular to the test surface [6].

8.2.2.2 Gap Probes

Also known as 'horseshoe' probes, these probes consist of a U-shaped ferrite core surrounded by a pair of coils around each end. Unlike bobbin wound probes, these probes induce flux lines that propagate from opposite poles of the U-shape. This mode of propagation yields higher sensitivity to planar discontinuities while being relatively insensitive to defects that lie perpendicular to the surface. As shown in Figure 8-3, these two types are coils can be used complimentarily to cover a wider range of possible defects.

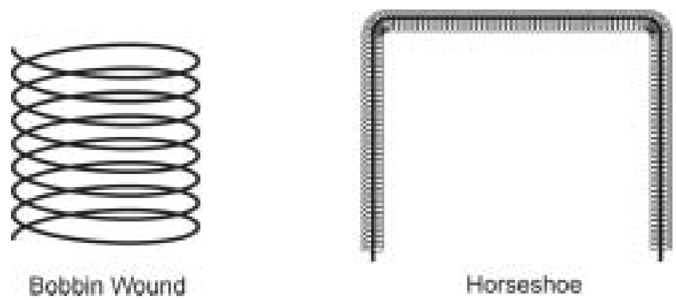


Figure 8-3: Major coil types in ET

8.3 TECHNIQUES AND APPLICATIONS

Despite the fact that ET cannot be considered one of the predominant methods for NDE of CFRP materials, a number of research projects have proven its applicability. Oftentimes, it is used as a complimentary method to confirm results of other, more established test methods, such as radiographic or ultrasonic testing.

Experimental investigation of eddy current tests on CFRP include those discussed in references [47], [48], [49], and [50]. To obtain a comparison between results from ET and UT, Lane et al. [47] investigated CFRP samples in a $[0/90]_s$ stacking sequence under influence of impact, tensile failure as well as simulated delamination. Results showed that ET is not capable of detecting separation of composite plies, which was attributed to the absence of fiber damage. Contrary, fiber breakage as a result of impact damage was detectable, even though low energy impact required UT as a complimentary method. Finally, tension tests were performed to study the effect of deliberate fiber failure on eddy current signals. It was found that there is good correlation between visual fiber damage and signals obtained from the ET system. It was concluded that, unless fiber fracture was the predominant failure mode, ET displays itself as more suitable in terms of discriminations than detection of damage.

Similar results were obtained by Degtyar and Pearson [48]. They investigated 0.25 in thick filament-wound graphite/epoxy rocket tubes upon the detectability of impact damage. Initially, UT measurements were obtained to provide a baseline for comparison. A 3/8 in radius coil, operated at a single frequency of 2 MHz, was utilized to scan the 4x4 in specimens that were previously impacted at various energy levels. Results showed little variation in impedance of the pickup coil with only slight deviations over regions where fiber damage had presumably occurred. This presumption was later confirmed by baking off the matrix and deplying the laminate layer by layer. It was concluded that ET

provides complimentary information on damage in impacted CFRP specimens but should not be chosen as the primary inspection method.
Further studies are reported by Gros et al. [50] who investigated ET and UT upon their suitability for detecting delamination in 0.04 in thick quasi-isotropic CFRP plates. Unlike the typical modeling approaches used in other NDE-studies, delamination was initiated by causing interlaminar ply separation between -45° and 90° plies under application of uniform tension. It should be emphasized that this form of delamination is inherently different from delamination induced by nonbonding material such as Teflon sheets, since delamination caused by tensile loading is not necessarily restricted separation of plies, but can further result in damage or rupture of fibers. Although sensitivity of ET in detecting delamination was shown to be lower than in UT tests, most defective regions could be located and characterized to a certain extent. Whether ET signals were caused by interlaminar ply failure or fiber rupture in the vicinity of delamination was not clearly addressed.

8.4 CAPABILITIES AND LIMITATIONS

Although most effort in the arena of eddy current inspection has focused on metallic components, use on CFRP has recently found increasing attention. Similar to ultrasonic testing, ET systems have steadily become more compact in size and have reached a high level of sophistication in terms of data acquisition and operation modes. Even though spot checks are usually performed manually, probes can theoretically be incorporated in an area scan unit, which can feed data into secondary processing devices such as a laptop. As a purely nondestructive method, no solvents, couplants or other substances must be applied to the surface in order to take measurements. The non-ferromagnetic nature of composite materials further aids in obtaining deeper penetration into the material. During in-situ inspections, results are usually available in real time, such that assessments on serviceability can be made instantaneous.
As outlined in the previous discussion, ET entails characteristics that allow only very specific inspection of CFRP composites. The fact that magnetic flux can only develop in regions of high fiber density presents one of the most significant limitations of ET. Although fiber damage can be characterized in most cases, damage related to matrix cracking or nonconductive material inclusions, such as sand or oils, remain largely undetected. In applications where reliability is mainly governed by the tensile properties of the composite, the method provides suitable information on serviceability since tension members experience failure primarily by fiber rupture. In bond applications, however, interply separation is more critical than fiber rupture, since fiber rupture is rarely experienced in externally bonded strengthening schemes.
In conclusion, ET may be capable of providing supplementary information on localized damage where fiber damage is either predominant or has been caused as a result of a secondary damage mode (impact, ply separation in tension, etc.). It should not be considered a method that can provide comprehensive insight on composite, and in particular, bond strength of composite systems.

9 MICROWAVE TESTING

Like infrared- and x-radiation, microwaves are a form of electromagnetic radiation characterized by a distinct frequency band. Traditionally, the microwave domain is considered to encompass electromagnetic frequencies roughly between 300 MHz and 300 GHz. In the electromagnetic spectrum shown in Figure 1-4, this yields wavelengths of 10^2 to about 10^{-1} cm [51]. As may be seen, this region coincides with that classified as ‘radar’. In fact, the entire range of individual frequencies, including TV, radar, and FM radio are regarded parts of the microwave frequency band. In the lower end of this range, spatial resolution of microwaves is thus in the order of 1 mm, which indicates their ability to discern closely spaced material features

The imaging capabilities of microwaves is based on transmitting highly directed electromagnetic waves into a dielectric material and using the information of magnitude and phase to create images of the specimen [52]. Since penetration of microwaves into conducting materials can be considered minimal, they are commonly applied only to non-conducting materials. As discussed in earlier chapters, carbon fibers classify as conductors, hence, there is a significant restriction in using microwaves as a transparent media, especially in examination of relatively thick components. However, microwave NDE has found application in thick non-conductive composites such as GCFRP plates with thicknesses of up to 100 mm [52].

While microwave NDE has not found appreciable attention in the civil sector, a more pronounced body of work has been established in the more specified field of radar testing, with particular focus on ground-penetrating radar (GPR), to be discussed in Chapter 14. Although it has been shown that applicability of microwave NDE to carbon-epoxy laminates is limited, this report will provide a detailed review on use of GPR towards characterization of civil infrastructure. Since radar has already found implementation into field methodologies, the authors feel that this review serves a more comprehensive understanding of radar technology and can thus aid in assessing its apparent limitations in NDE of CFRP-rehabilitated components.

10 OPTICAL METHODS

10.1 FUNDAMENTALS AND THEORY

The field of optical testing entails a large variety of individual sub-methodologies that allow detection of almost infinitesimal surface deflections through formation of fringe patterns on the surface of an object. Limited by the wavelength of light, displacements of fractions of 1 μm can theoretically be measured [53]. Some of the most frequently applied methods include moiré interferometry, holography, and shearography.

Basic optical methods, such as geometrical moiré [54], utilize superposition of two gratings to cause formation of fringe patterns. Similar to lines on a contour map, lines formed by moiré interference correspond to regions of equal displacement relative to a fixed reference point. Depending on number and frequency of fringes in an area, one can derive the magnitude of in-plane displacement and corresponding strain in the material. Figure 10-1 illustrates fringe patterns resulting from superposition of a stationary (vertical) grating with a rotated (a) and horizontally strained grating (b), respectively. If the point of zero rotation and zero translation is defined to be located at fringe N_0 for the left and right image, respectively, each adjacent fringe is representative of a specific incremental rotation/translation. The absolute value of these displacements depends on the spacing between individual lines on the grating, denoted as *pitch*, which is the main factor governing sensitivity of optical methods.

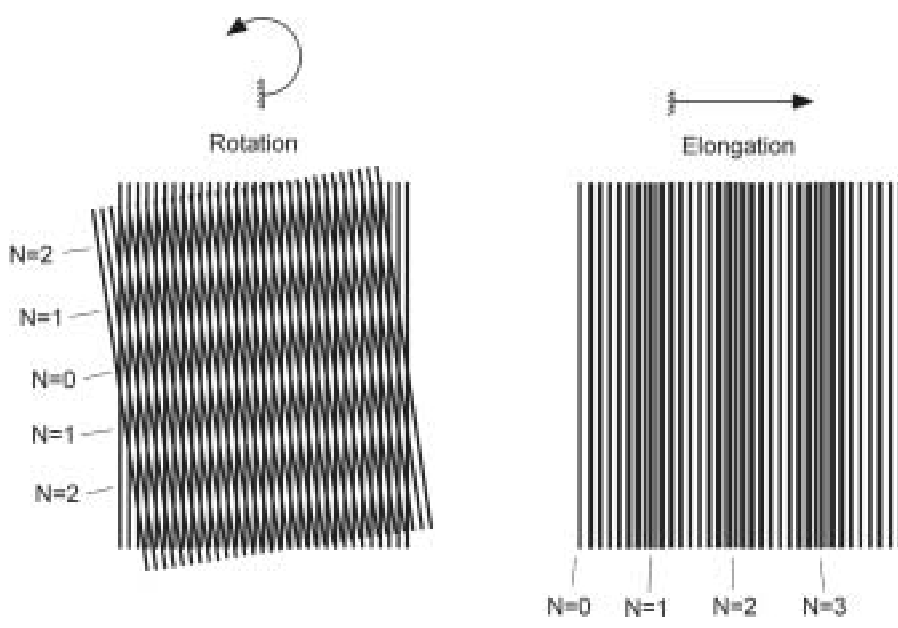


Figure 10-1: Moiré Fringes caused by (a) Rotation and (b) Translation

In geometrical moiré, sensitivity soon reaches its limitations due to the maximum number of lines that can be physically situated on a unit length of material. To obtain a significantly larger line frequency, the principle of optical interference of *coherent* light can be employed. As illustrated in Figure 10-2, interference of two coherent light beams results in regions of constructive and destructive interference, i.e. regions of presence and

absence of light. If two of such gratings are superimposed, interference patterns of extremely high detail will result.
To investigate displacement or strain on an object surface, a *specimen grating* must be attached directly to the object itself. In most cases, this is done with a special adhesive that is chemically formulated to provide full strain compatibility with the test object without causing a chemical or reinforcing effect to the object itself. A second grating, commonly known as the *master grating*, is situated between the specimen and the observing/recording media. During testing, a superimposed image of both gratings is recorded at distinct time instances. Preferably, these are instances of varying load levels, to allow interpretation of minute differences between the individual images. In all tests, one desires to relate the fringe arrangement to the actual displacements/strains in the material. While displacements and strains become readily available from the number of fringes over a certain area, stresses can also be obtained, assuming that material properties are known. Since most material anomalies induce stress concentrations to the host material, strain in such regions will deviate from that of a sound area. In many cases, strain patterns can be interpreted to detect material flaws, even if they are located inside the material [55], [56], [57].
As may be seen from Figure 10-1 b), the resulting fringe patterns only reveal information on displacement and strain of the object in a single direction. Since the grating is oriented parallel to the y-axis, any object deformation along this axis would not cause alteration in the fringe patterns. To overcome this drawback, a cross grating can be applied to the specimen. However, this also necessitates two separate master gratings, oriented along the two principal axes.

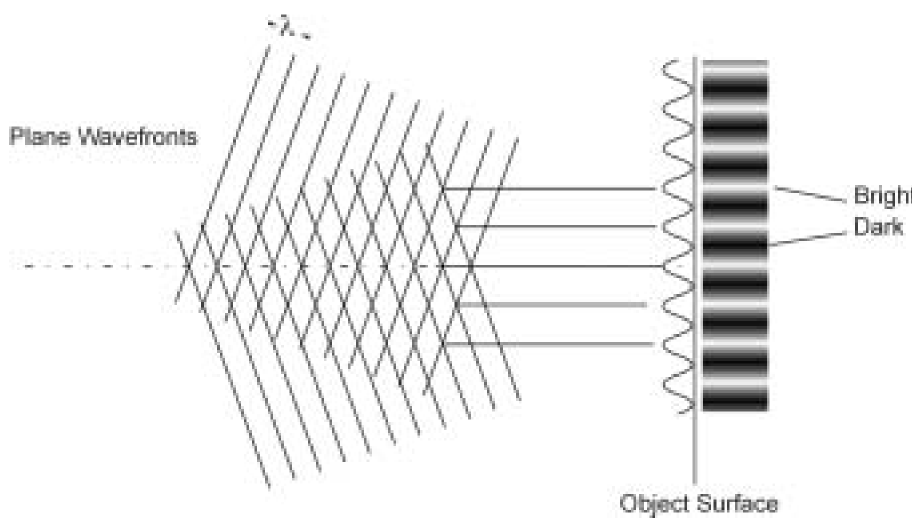


Figure 10-2: Interference of coherent light beams

Unlike all of the previously discussed methods, optical techniques require a stress to be imposed onto the material such that fringe patterns can be obtained. Hence, optical methods are inherently different from classical NDE techniques in that they necessitate application of an external or internal load, which can be of either mechanical or thermal nature. For evaluation of adhesive bonds, it has been shown that detectability is often more pronounced under thermal loading [56]. Other methods of external excitation include vibration, microwave or impact. For optical methods to remain truly nondestructive, the level of loading must not be taken to a level at which permanent deformation can be expected. Due to the high sensitivity set forth by the nature of light, minute strain levels are often sufficient to display most anomalies.

For defect analysis, advanced optical measurement techniques allow the continuous recording and evaluation of data via digital equipment, which led to an increased interest in this form of NDE testing. In earlier applications, results could not be obtained in real time due to limitations imposed by the development process inherent to photographic films. Lately, digital acquisition has led to the ability of real-time imaging and more rapid quality assessment. This development has also increased the attractiveness of optical testing for in-situ applications. Particularly, the development of lasers has contributed significantly to the broad utilization of optical techniques. The fact that lasers emit *collimated*, coherent light makes them particularly useful for optical measurements. As such, lasers have found particular attention in speckle interferometry, a method mostly suited for out-of-plane measurement.

As opposed to the more sophisticated optical methods, geometrical moiré has found limited implementation into automated processes. In most applications, interferometric methods are given preference, mostly due to their extremely high sensitivity. In the following, only processes that show particular potential for incorporation into automated and rapid processes will be discussed in more detail.

10.1.1 Moiré Interferometry

Interferometry combines methodologies of geometrical moiré with a more complex setup, thus allowing even higher resolution and flexibility. Since gratings in moiré interferometry are formed by optical interference of laser light, it provides whole-field patterns of high spatial resolution with a sensitivity of 2.4 fringes per μm [58].

In moiré interferometry, the master grating is formed by interference of two coherent light beams that obliquely illuminate the specimen at two complimentary angles α. These beams typically originate from a single remote laser source whose beam is separated by means of beam splitters and broadened/redirected by beam expanders and several mirrors. Due to coherence, the beams generate walls of constructive and destructive interference, which results in a virtual grating in the zone of their intersection [58]. Although interference of these walls is not visible in space, it can be made visible once the waves intersect an object and are reflected off its surface. Hence, the specimen grating is of physical nature while the master grating is created virtually through light beam interference. A conventional setup for interferometry measurements is depicted in Figure 10-3.

As outlined in the previous discussion, complete full-field strain analysis requires two gratings with lines oriented perpendicular to each. Such setup can be obtained from two beam-pairs, while a cross grid substitutes the formerly utilized linear specimen grating. Hence, one may obtain strain profiles in two orthogonal directions.

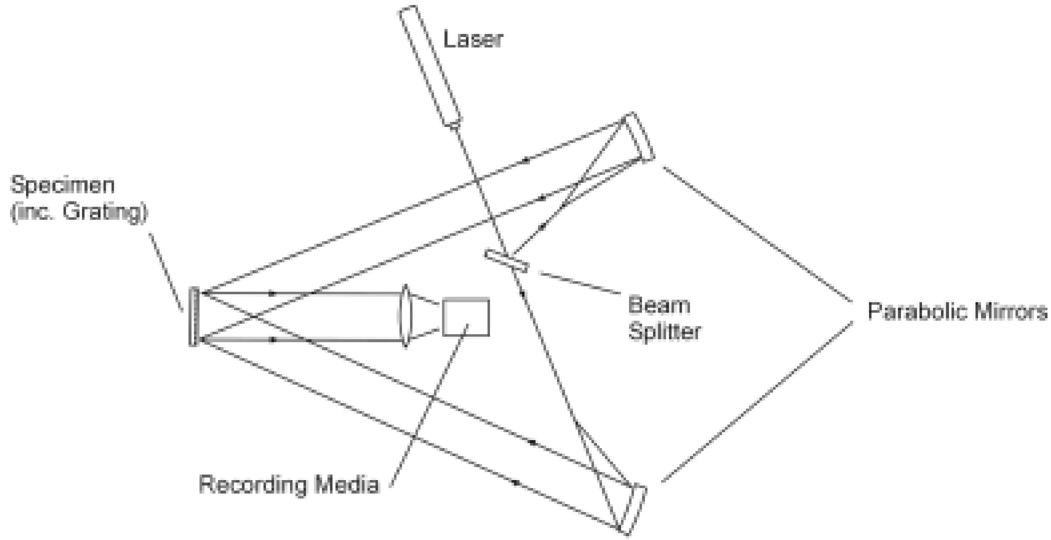


Figure 10-3: Setup for moiré interferometry

10.1.2 HOLOGRAPHY

Compared to moiré interferometry, holographic interferometry (Figure 10-4) utilizes a slightly different test setup, which provides the possibility of creating perfect three-dimensional images from a body. Instead of causing interference of two beams in close proximity to the object to form a virtual grating, a reference beam is aimed directly at the recording media, while a second beam illuminates the test object. The preferably white surface of the object causes reflection of the scattered light waves towards the recording device where interference of the two beams occurs. In real time holography, results can be obtained instantaneous by looking at the image of the unstressed object superimposed on the stressed object [59].

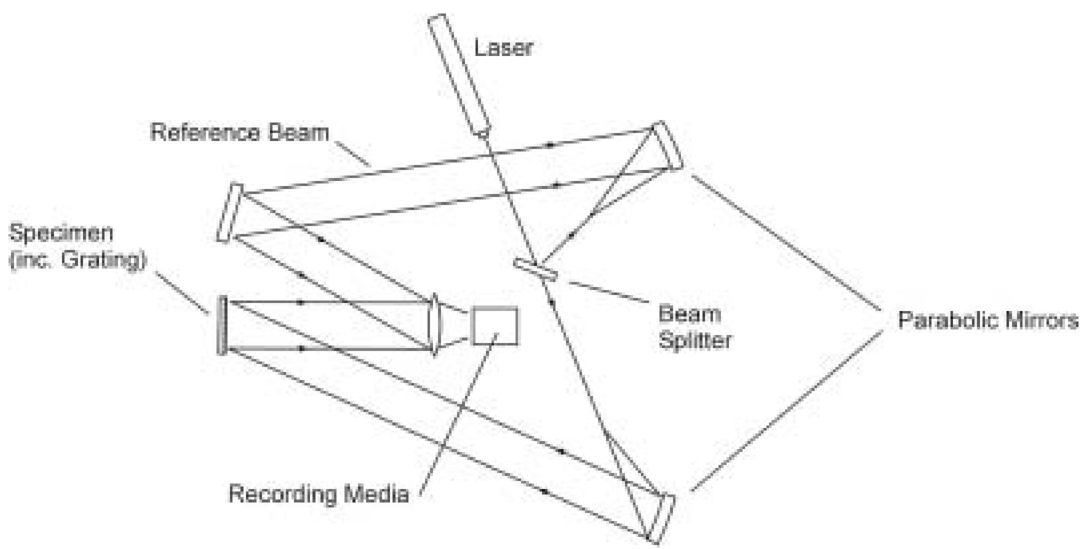


Figure 10-4: Test setup employed in Holography

A significant advantage of this method lies in the fact that it does not necessitate a specimen grating, which might become undesirable especially due to practical or aesthetic restrictions. However, holographic testing has stringent stability requirements that are often difficult to assure in the field. Thus, this technique has mostly found application in laboratory experiments [59].

10.1.3 SHEAROGRAPHY

Succeeding the introduction of the laser, its *speckle effect* caused a considerable amount of disappointment for many years. Causes for this effect lie in the minute roughness of any surface that is not ideal specular [53] and are experienced in form of a grainy structure on any object surface that is illuminated by coherent laser light. As in the previously discussed optical methods, scattering of coherent light from a single broadened laser source causes points of interference in the image plane in form of speckles. Recently, the potentials of this phenomenon have been employed in form of shearographic imaging of surface strain fields.

The key to object study in electronic shearography is a birefringent crystal that serves as a shearing device. This shearing crystal brings two nonparallel beams scattered from two separate points on the object surface to become nearly colinear [56]. As in sections 10.1.1 and 10.1.2, images taken at two different time instances display a slight alteration in intensity distribution and are thus related to surface strains. As a result of image subtraction, their differences can be visualized.

Shearography entails certain distinct advantages over moiré interferometry and holography, which are summarized as follows [56], [55]:

- It employs a simpler optical setup
- Since no reference beam is required, it alleviates the stringent environmental stability typically necessitated in holography
- It provides a wider and more controllable range of sensitivity
- It measures displacement-derivatives, which are directly related to strain, whereas interferometry and holography measure absolute displacements

Similar to moiré interferometry and holography, flaw revealment in shearography is based on the comparison of two states of deformation in the test object. While it is ideal to impose stresses similar to those found under service conditions, they sometimes induce intolerable rigid-body motion, causing decorrelation of the speckles in the two images resulting in degradation of fringe quality [56]. A number of loading techniques are known that do normally not produce the intolerable rigid-body motions, including pressurization, thermal stressing, vibrational excitation or impact stressing. The schematic setup of shearography is depicted in Figure 10-5.

10.2 INSTRUMENTATION

Depending on the optical method and individual setup, a range of components is needed to complete an optical imaging system. However, most setups are comprised of an illuminating system, a set of beam splitters/expanders, mirrors and lenses, as well as the recording media. In the following, vital components will be discussed briefly.

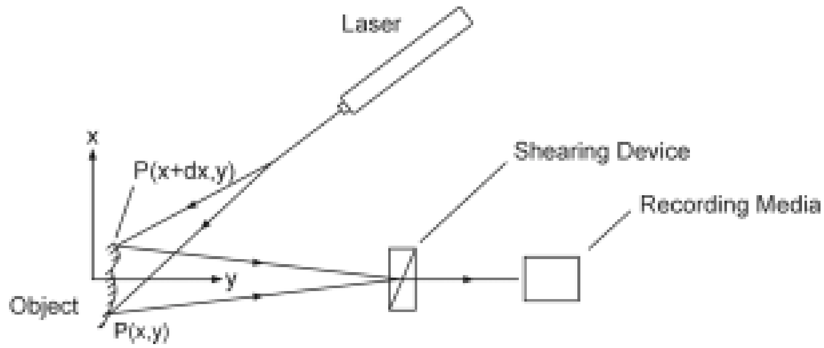


Figure 10-5: Setup for shearographic imaging

10.2.1 Light Sources

An important variable of light sources for technical applications is their bandwidth, which describes the range of wavelengths that are emitted from a source. In conventional helium-neon or argon-ion lasers, the bandwidth lies in the order of 10^{-6} nm (10^{-15} m), resembling an extremely small range of dominant frequencies. Consequently, the output is comprised of a single wavelength of 632 nm, 514.5 nm or 488.0 nm, for red, green and blue-green lasers, respectively. Secondly, laser light is said to have high *spatial* and *temporal coherence*. These characteristics relate to the fact that waves are created in the laser at almost the same instance in time as well as at the same point in space. Lastly, the laser output beam is so well directed that it can be considered a perfect point source, whereas most other sources are extended sources due to their significantly broader emission [58]. Today, laser sources are readily available and particularly tailored for many applications in research and industry. Although lasers are much more expensive than conventional light sources, they offer unsurpassed possibilities for optical testing. For use in mobile units, small laser diodes have been developed that run at about 50 mW and are capable of covering areas of up to 400x400 mm^2, provided that the system is not operated in direct sunlight, since this can greatly reduce fringe contrast [60].

10.2.2 Prisms and Partial Mirrors

To reduce complexity of an optical setup, it is preferable to utilize only a limited number of light sources. Hence, in most systems, beams are split and redirected at various locations along their path. To separate a coherent beam, the incident light wave is directed at a highly thin film deposited on the surface of a glass body, which acts as a semi-transparent media. As a result, specific amounts of the incident light wave are reflected and refracted. The ratio of both values depends mainly on the thickness of the coating. One concern in utilizing beam separation lies in the consequent reduction of light intensity with formation of a new branch. However, most laser sources provide sufficient energy to allow splitting of one beam into multiple ones.

Through laws of reflection and refraction, the exact direction of emergence of an incident beam can be prescribed [53]. For small angle refraction, wedges are typically used, while prisms provide stronger refractive characteristics for large angle changes (Figure 10-6).

Being a semi-transparent mirror, beam splitters are essential. These partial mirrors have become an integral part in almost every system where two beams are caused to interfere.

10.2.3 Recording Media

Generally, two forms of recording media are available for storage of optical data. As in conventional photography, perturbation of fringe patterns can be permanently recorded on photographic film that is exposed prior and after an incremental load has been applied to the test specimen. Although it provides high resolution and a permanently recorded image, one significant disadvantage of this process is its incapability of real time imaging. This drawback has been overcome by the introduction of digital CCD equipment that allows continuous recording of fringe patterns. Data is successively fed into a frame grabber that can be integrated into most modern computer systems. This enables the inspector to perform both on-site analysis as well as post-test analysis for detailed observation.

When laterally sheared images are forced to interfere with one another, each pixel of the CCD device acts as a separate strain gauge, indicating output capabilities of up to 250,000 real-time adjacent strain gauges [13].

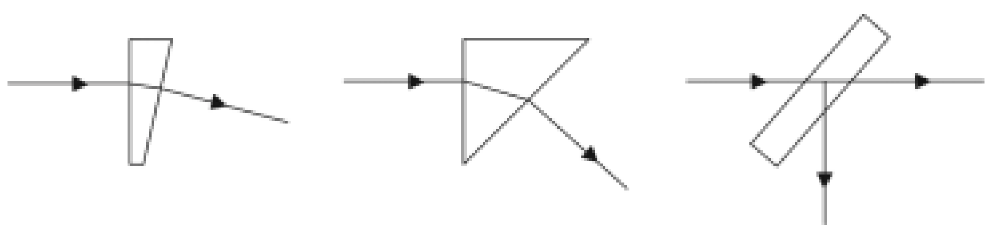


Figure 10-6: Common methods for beam modification:
wedge (left), prism (middle), and beam splitter (right)

10.3 Techniques and Applications

As outlined in the previous discussion, shearography can be clearly identified as an optical method that entails most potential for actual in-situ applications. Although interferometry and holography are suitable methods for laboratory testing, their stringent stability requirements imposed on the optical system can seldom be met in field applications. As a result, the subsequent discussion on previous experimental work will be focused on shearography exclusively.

Despite being a fairly young technique, shearography has already received considerable industrial acceptance for nondestructive inspection. Examples include testing of automotive tires, evaluation of pressure vessels, adhesive bonds as well as composite panels for the aerospace industry [56]. For on-aircraft use, portable systems are already in use worldwide [13].

Hung [56] demonstrated inspection of a composite filament wound pressure vessel by means of internal pressurization as well as core debonds on a Boeing 747 wing flap. Along the perimeter of the vessel, four fringe patterns were obtained at 90° increments that led to the detection of impact damage in several regions. The wing flap was made of 0.072 in thick graphite skin bonded to a honeycomb core of about 2 in thickness. Under external vacuum imposed by a suction cup, debonds were detected. The rate of inspection for this specific application was reported to be 0.5 sq. ft in less than 10 seconds.

Gregory [13] addressed the current applications of shearography to inspection for aircraft and space structures and, in particular, inspection of CFRP sandwich panels containing ventilated Nomex cores. Components were comprised of ten carbon fiber layers with disbond size ranging from 6.35 mm (1/4 in) up to 10 mm (5/8 in) diameter. Hot air emitted from a heat gun was used as the stressing medium, raising the surface temperature by only 3-4ºC. During an overall inspection period of only 30s, disbonds of all sizes were detected.

Particularly in the civil sector, shearography must be considered a novice technique that has not yet experienced similar industrial widespread or acceptance as ultrasonics or thermographic imaging. Moreover, most experimental work and field inspections are performed under controlled laboratory environments, which are often inherently different from those encountered in the field. Confirmation of applicability to civil environments thus remains an objective of future research.

10.4 Capabilities and Limitations

Shearography is a whole-field non-contact method which, although fairly recently developed, has already gained significant acceptance as an NDE method. Depending on the intensity and broadness of the incident laser beam, large areas can be inspected simultaneously, which results in a less time consuming process. Currently, test units that incorporate CCD camera, a shearing device and a laser diode are only about 200x60x80 cu mm in size and weight less than 1 kg [60]. Hence, they are mobile and can be easily set up in the field.

A significant prerequisite for shearographic imaging, and in fact most other optical methods, is the fact that a component must be loaded to allow the recording of displacement derivatives. While this imposes certain flexibility restrictions, it ensures that the structure is inspected under real-life conditions in that it is exposed to one or multiple actual loading situations. It further yields that only those defects, which are of sufficient dimension to cause stress concentrations in the material, will be sensed. One may further argument that those defects that are not imposing stress concentrations into the composite or the adhesive bondline may very well be classified negligible in terms of their criticality. Hence, the technique is able to differentiate between relevant and cosmetic defects [13]. Nevertheless, for a comprehensive characterization of all defects, regardless of criticality, a second complimentary method should be utilized.

As outlined, optical methods are limited to surface inspection that limits defect detectability to those anomalies that are of sufficient size or shallowness to induce stress concentrations into the surface. While this is a significant drawback for inspection of thick composites, it is less critical in thin or honeycomb composite structures with a more flexible core material. Nevertheless, experience in signal interpretation is indispensable for characterization of subsurface defects. In addition, even though regions of increased strain may be identifiable, their characterization with respect to defect type can be of more difficulty.

11 ACOUSTIC EMISSION

11.1 FUNDAMENTALS AND THEORY

Acoustic Emission (AE) has been applied extensively to provide real-time information on damage progression in mechanically loaded components [61], [62], [63]. Similar to optical methods, AE is a *passive method*, whereas most other NDE techniques are considered *active*†. In fact, acoustic emission cannot be considered truly non-destructive, since acoustic signals are only emitted if a permanent, non-reversible deformation occurs inside the material. As such, only non-reversible processes that are often linked to a gradually progressing material degradation can be detected using AE. Nonetheless, acoustic emission has found wide acceptance for industrial use, such as pressure vessels and tanks [6], hybrid CFRP-concrete columns [62], as well as bridge stay cables [63].

As a material is stressed, energy is first released in regions where stresses are sufficiently high to cause new, permanent deformation. This deformation can occur on the atomic level as well as on a macroscopic scale and since it is more likely to occur in regions of material anomalies, AE signal are commonly first emitted from defective regions with deficient integrity. Once a signal is given off, it propagates in form of high-energy stress waves, similar to those found in ultrasonic testing. Through the use of adequate sensors (transducers) a wave of mechanical energy can be recorded and electronically amplified for further analysis by suitable AE equipment.

Under most loading conditions, regions of discontinuous composition tend to experience some form of stress concentration. In these regions energy is stored in form of a high local stress field. In fiber composites, these stress concentrations can reach levels as high as nine times the average full-field stress. When the material cracks at internal discontinuities, a new surface is formed and the stored elastic energy is released in form of heat as well as a short pulse of elastic and kinetic energy that travels from the defect and disperses into the material. Although the frequency spectra of stress waves theoretically ranges from a few hertz to 1000kHz and higher, experience has shown that transducers operating between 100-500kHz provide sufficiently high sensitivity to most relevant AE events [6].

Once the acoustic signal has been emitted from a source inside the material, a process that typically lasts no longer than a few millionths of a second, it propagates in all directions. Velocity and directionality of propagation are material-specific, as discussed in Section 5.1.1. In many aspects, wave propagation in acoustic emission follows the same physical laws as those prescribed for ultrasonics. As such, high frequency signals tend to experience attenuation in form of dispersion (geometric spreading), reflection (scatter) and absorption. Especially composite materials inhibit a large number of interfacial boundaries at which signal scattering and absorption can reduce signal intensity and impose difficulties in obtaining a clear and differentiable signal. Also, waves tend to propagate along the fiber direction, making composite materials more preferable for signal detection over relatively long distances [63].

Once an acoustic signal has propagated from its source to reach the object surface, piezoelectric probes can be used to convert the mechanical stress waves into an electrical signal presupposing that the wave has not attenuated to a level below the sensitivity of

† *Active* refers to the emission of some form of energy, whereas *passive* methods draw all signal energy from externally applied loading, in either mechanical or thermal form.

the transducer. Herein, good contact between the surface and the probe is essential in obtaining a high amplitude signal. Acoustic couplants are typically in form of a gel-like substance that is applied to the sensor face as a thin film. Subsequently, the sensor is pressed against the surface and securely held in place with adhesives or similar means. This ensures a low impedance gradient between the test object and sensor surface, as this is essential for most of the wave energy to be transmitted to the transducer surface instead of being reflected back into the bulk material.
All electronic signals collected from the piezoelectric crystal in the transducer are transformed into a voltage level, which is proportional to the amplitude of mechanical excitation. In other terms, the output voltage amplitude varies linearly with the input motion amplitude [6]. Once a mechanical wave arrives at the transducer surface, causing deformation to its piezoelectric crystal, a short voltage spike is sent to an electronic acquisition device, which filters and amplifies the signal to reduce low frequency background noise and to obtain a voltage level that is optimum for the circuitry of the AE instrument. In order to collect solely information representative of significant events, the user can preset a voltage threshold by which the system ignores events that fall below the specified voltage amplitude.
Signals are characterized by their four main parameters, namely amplitude, duration, energy and counts. Each resembles a specific characteristic of the incoming signal where correct interpretation of one or multiple of these parameters is dependent on experience and analytical potential of the inspector. Because data is continuously streaming to the memory of the AE system, a multitude of analytical graphs can be displayed in real time.

Difficulties in AE testing arise from the fact that discrete bursts can originate from a variety of sources. This aspect is especially critical in hybrid structures where two or more materials are forced to interact, because signals can be initiated in either material or at their joint interfaces. With respect to CFRP-concrete hybrid structures, a number of AE energy sources are known, including cracking, plastic deformation, friction of aggregate interlock and mortar/aggregate debonding in concrete along with fiber/matrix debonding, matrix cracking, delamination and fiber breakage in composite laminates [62]. If both materials are joined, debonding must be considered as a further signal source.
Apparent damage in materials is often derived from presence of the *Kaiser* and *Felicity* effect [62], which are related to the appearance of AE signals in successive loading and unloading. A material that experiences the Felicity effect is said to emit acoustic signals at loads below that of the previous stress level. Conversely, the Kaiser effect postulates absence of any signal until the previous load is exceeded. A qualitative representation of this is depicted in Figure 11-1. As the material is loaded, the number of total events increases from zero up to point A. During a short unloading phase (A to B), no further acoustic signals are emitted. Upon reloading, materials following the dashed line begin to emit acoustic signals at a load below that of the previous level and are thus said to experience the Felicity effect. Conversely, the solid line returning to point A with subsequent increase in acoustic events represents materials governed by the Kaiser effect. From previous studies, it has been shown that concrete experiences the Kaiser effect to load levels up to 75-85% of its ultimate strength [62]. In contrast, fibrous composites are

known to emit AE signals at significantly lower stress levels as those encountered during previous cycles and are thus governed by the Felicity effect.

11.2 Instrumentation

AE inspection systems envelop a fairly small number of components that are all highly mobile and simple to operate. As most other computer assisted testing methods, software and acquisition devices can be incorporated into most modern computer systems, which makes AE highly favorable for use in the field. Transducers used for signal capturing are generally identical to those discussed in Chapter 5 and will therefore not be further addressed here. Nonetheless, it should be pointed out that transducer are commonly selected based on their natural frequency of vibration, since it determines which frequency range they are most easily excited by.

Apart from the transducers, typical systems are comprised of one signal preamplifier per channel as well as a central AE unit that records and analyzes the incoming data stream.

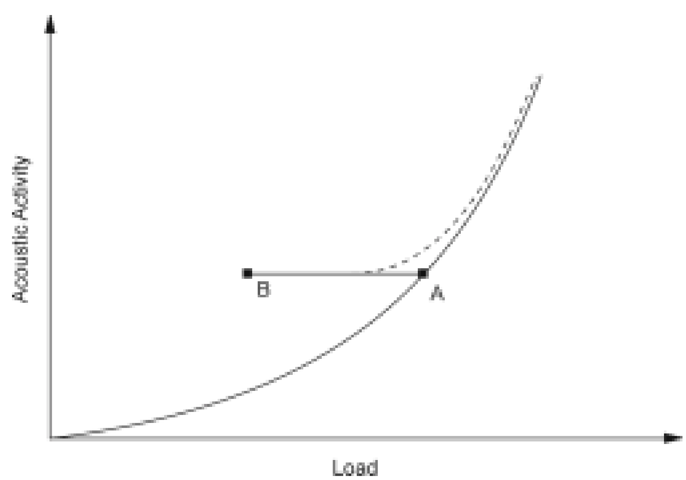


Figure 11-1: Graphical representation of the Felicity and Kaiser effect

11.2.1 Preamplifiers

Preamplifiers, as shown in Figure 11-2, are used in most systems that use transducers that do not already have preamplifiers incorporated in them. A typical voltage spike produced by a piezoelectric crystal is of insufficient amplitude for the acquisition system to record. Thus, a preamplifier is used to boost the signal to about 40-60 dB, depending on individual test conditions.

11.2.2 Software and Data Display

Data display in AE is inherently different from other NDE techniques. Rather than displaying visual images, the numerical data is graphed. Most software packages provide the user with a number of possible graphs to display during testing such that acoustic activity can be monitored in real time. The most common graphs are amplitude-time, energy-time or event-time.

Figure 11-2: AE preamplifier and transducer sample (inset)

Figure 11-3: AE data acquisition system

11.3 TECHNIQUES AND APPLICATIONS

Because AE tests do not provide the inspector with visual information comparable to that obtained from radiography or thermographic imaging, other characteristics unique to AE must be employed. Problems mostly arise from the fact that it is often not possible to predict type, shape or exact location of a defect by simple acquisition of acoustic wave signals. Difficulty in signal interpretation is even more pronounced in testing of composite materials, where anisotropy causes wave fronts to disperse at different velocities depending on its specific lay up sequence. In unidirectional composites, however, fibers often act as wave guides such that signals can travel over longer distances [63]. On the other hand, if sensors are positioned at a distance from the signal source and perpendicular to the fiber direction, strong signal decay is almost unavoidable.

Prior to testing, the system setup, encompassing preamplifier setting and positioning of transducers must be checked by inducing an artificial acoustic event. Such calibration is most commonly performed via a simple pencil lead break (Figure 11-4) in which the tip of a pencil is broken near the region of an expected defect. Since frequencies produced by fracturing of the lead tip are similar to those encountered from internal material fracture, system sensitivity can be adjusted to an acceptable amplitude threshold.

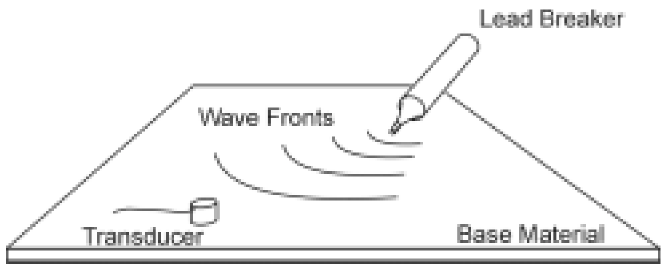


Figure 11-4: The lead-break test

Apart from the four main signal parameters listed in Section 11.1, signal frequency provides valuable information on signal source type. Experiments have shown that frequency content of AE signals can be associated with particular forms of damage [64], [65]. Frequency separation can be advantageous in determining the cause of failure in composite materials, since fibers and matrix possess significantly different material properties. For CFRP, frequencies in the 90-180 kHz region are proposed to be representative of matrix cracking, 180-310 kHz for fiber pullout, while higher frequencies correspond to fiber fracture [65].

Since an acoustic signal can originate from anywhere in the material, source location is AE is difficult. However, information on source location can be provided through attachment of multiple sensors and comparing the arrival times of one specific event. While this is a feasible method in isotropic materials, a variation in wave velocity restricts source location to quasi-isotropic composites.

Examples of previous AE experiments include investigation of glass- and graphite-epoxy dog bone specimens in static and fatigue loading [66] as well as tests to study cracking mechanism in concrete [67], [68].

Damage progression monitoring in ref [66] showed that fiber fracture could be clearly identified from other acoustic activity, while matrix cracking could not be clearly distinguished. Further, fatigue tests indicated that most of the acoustic signals are emitted within 90 to 98 percent of the fatigue life of the composite, which is promising in terms of long term failure monitoring of CFRP composites.

Investigation in reference [63] was aimed at introduction of AE as a permanent monitoring system for CFRP bridge stay cables. Cables of varying diameter and average length of about 5650 mm were exposed to dynamic fatigue tests and monitored with two AE transducers positioned at each end. Results showed that, despite their enormous length, CFRP cables are excellent waveguides exhibiting relatively low attenuation.

Lastly, Mirmiran et al. [62] evaluated acoustic emission towards applicability for monitoring of hybrid CFRP-concrete columns. Columns measured roughly 150 mm in diameter and were encapsulated by bonded and unbonded GCFRP shells. Cyclic compression tests showed a significant Felicity effect for both bonded and unbonded shells with even a slight increase in energy level during the unloading phase. Overall, signal activity was more pronounced for unbonded shells, which was attributed to friction developed at the core-shell interface.

11.4 CAPABILITIES AND LIMITATIONS

Compared to other NDE methods, the significantly different nature of acoustic emission testing implies certain advantages and disadvantages. Firstly, the rather simplistic setup of an AE monitoring system allows on-line life monitoring of existing structures. In anisotropic materials, such as CFRP cables, AE has already been proposed as a permanently installed health monitoring system [63]. Secondly, the method allows global monitoring without altering the setup parameters. As such, no repetitive inspection routines have to be performed, which represent a source for errors, assuming that inspection personnel as well as routines may be altered or changed over time. Also, since AE systems are favorable for long-term monitoring, they offer the incorporation into remote data acquisition systems from which data can be transmitted to numerous receivers simultaneously. Remote sensing can be especially advantageous in structures with a high demand public demand, such as bridges, dams or high-rise buildings. In case of an earthquake or fire, serviceability can thus be assured more rapidly.

Limitations in AE testing arise from a number of factors. Primarily, meaningful AE testing can only be performed on members that undergo some sort of material degradation, which separates the method from most other NDE techniques as not being truly nondestructive. In addition, signal emission is a unique occurrence that is not repeatable once the material has permanently deformed. Also, if signals are acquired, they can originate from a number of sources, including friction at interfaces [62]. As such, the AE signal-time history must be monitored and recorded continuously throughout a structure's lifetime, which demands the incorporation of a system immediately following its erections. If testing is initiated at a later stage, damage that may have previously occurred will most likely go undetected.

Apart from these practical aspects, signal interpretation is far more difficult than in most other techniques. Due to difficulties in matching frequency response of the transducer with frequency content of the various AE signals, spectral analysis can be considered an ineffective tool for source determination [62]. In initially cracked components, signals can originate from newly developing damage as well as from friction at already existing fracture surfaces. Their exact distinction is a highly difficult task. Also, size, shape and type of defects can often not be clearly identified and because the acquired data is not mapped in ways similar to UT or thermography, much is depending on the inspectors' experience.

Summarized, acoustic emission should be regarded as a potential method for early failure detection and health monitoring of new or existing structures. However, it should not be considered to be of high potential for providing comprehensive insight on presence and progression of internal defects.

12 GROUND-PENETRATING RADAR

12.1 Fundamentals and Theory

In many aspects, the concept of ground-penetrating radar inspection is similar to that employed in air traffic control. In principle, an electromagnetic wave of variable frequency (500 MHz to about 1.5 GHz) is emitted from an antenna and directed at either a stationary or moving object. As the emitted signal encounters the object surface, part of it is reflected back and can be used to calculate location and, in case of a moving object, velocity [69]. In structural inspection, the object of interest resides at a fixed position in space, hence measurements of dynamic movement are not of primary importance. Instead, the electromagnetic wave, which is capable of penetrating materials like concrete, wood or masonry, can provide information on internal material discontinuities. While radar has long been applied to problems such as measurement of sea-ice thickness, profiling of lakes and rivers or geological surveying of the lunar surface, it has recently found application in detecting delamination in concrete bridge decks, caused by corrosion of the reinforcing steel [70] as well as moisture in masonry structures [71].

Within the electromagnetic spectrum (Figure 1-4), radar can be located adjacent to the infrared spectrum, indicating an average decrease in frequency of about three orders of magnitude. Because of its electromagnetic nature, extremely high frequencies are stringent for obtaining short wavelengths. For instance, excitation frequencies in the order of 1 GHz yield wavelengths of about 30 cm.

In principle, the propagation of the signal is affected by the dielectric properties of the propagation media, so that its attenuation and reflected components vary accordingly [72]. As the method relies on reflection of wave fronts from within the host material, theoretic assumptions regarding the laws of penetration and reflection, as discussed in Section 5.1.2 to 5.1.4 remain valid. Moreover, the general methodology of testing is mostly identical to that of ultrasonics. As such, a single antenna can be used to transmit and receive a signal as it is reflected off interfaces in the material. However, detectability of radar systems is dictated by differences in dielectric material properties instead of variation in acoustic impedance. Similar to acoustics, the coefficient of reflection for electromagnetic waves is as given in Equation 3, assuming the acoustic impedance's Z_1 and Z_2 are substituted with the electromagnetic impedance Z_e, denoted as

$$Z_e = \sqrt{\frac{\mu_0}{\varepsilon_0 \cdot \varepsilon_r}} \qquad (8)$$

As before, reflection and refraction of the incident wave will occur as the wave encounters in interface between two inherently different materials. As radar travels through the host material, its propagation velocity is described as

$$v = \frac{c}{\sqrt{\varepsilon_r \mu_r}} \qquad (9)$$

indicating the strong dependence on the relative dielectric constant, ε_r, as well as the relative magnetic permeability, μ_r. Further similarity between radar and ultrasonics can be noted by signal attenuation. Whereas attenuation in ultrasonics was primarily governed by a high impedance gradient at interfaces, magnetic permeability and conductivity of the propagation media predicate signal decay in radar inspection. It may be assumed that these fundamental differences impose new or alternative requirements onto the overall testing methodology of radar inspection.

Firstly, the stringent coupling requirements imposed on ultrasonic testing can be named as one of the most significant differences. Herein, one must consider that differences in electromagnetic impedance, which in turn dictates energy reflection at interfaces, are solely influenced by the relative dielectric constant, ε_r, of individual materials (compare Equation 8). Assuming a commonly encountered interface of air/concrete, these materials have relative dielectric constants of ε_r = 1 and ε_r = 6-12, respectively [70]. From Equation 8, one finds that roughly 50% of the energy is transmitted into the material, which eliminates the need to physically couple the antenna to the concrete substrate. Consequently, a variation of test setups can be used, some of which are shown in Figure 12-1. Illustrations depict typical measurement as performed in localizing internal steel reinforcement and zones of high moisture and chloride content in reinforced concrete slabs.

Secondly, only a limited range of materials allows inspection via penetrating radar. As such, applicability is generally limited to materials that are good electrical resistors, including sand, soil, water or concrete [72]. In conductive materials, i.e. steel or salt water, the rapid signal decay restricts deep penetration of the electromagnetic signal. Although ocean mapping is performed in a conductive media and should therefore be assumed to be problematic, the unusually long wavelengths contribute significantly to lower attenuation of the signal.

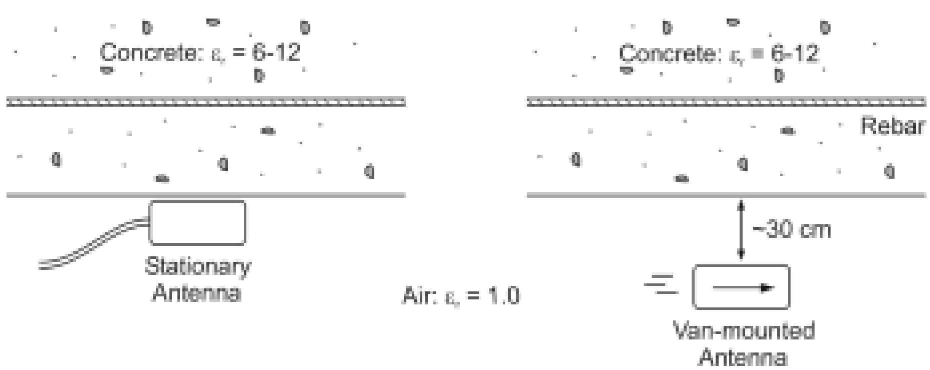


Figure 12-1: Various employable GPR setups

12.2 INSTRUMENTATION

Implied by the extensive use of radar equipment in the modernized world, these systems represent a well-established and highly specialized field. The primary components found in a radar system are a waveform generator, a single transducer comprised of an emitting and receiving antenna, a signal processor as well as a data storage/display unit.

12.2.1 *Generator*

Waveform generators are utilized to transmit either a continuous or pulsed sinusoidal excitation signal to the antenna, which is subsequently transformed into the test material. To adapt to a variety of test conditions, generators can cause excitation over the full frequency range. Depending on test approach, the transmitted frequency can be kept constant or swept within preset limits, as further described in Section 14.3. Relatively low energy consumption permits these units to be operated off a conventional 12 volt DC automotive battery, however, this adds significantly to the weight of the system [70]. Hence, these systems are restricted in their portability, as the total weight of a typical system may be about 25 to 30 kg.

12.2.2 *Antennae*

Configuration and layout of the antenna is largely influenced by the specific application. The most commonly applied configuration is that of a 'bowtie' dipole, providing a diverging beam that is most preferable when performing surface contact inspection. Alternatively, 'horn' antennas with a more focused beam, usually driven at 1 GHz, have been developed for special applications. Here, the beam is of a more focused configuration, which allows testing at increased distances. Horn antennas have found use in vehicle-mounted surveying of highway- and bridge decks, where the antenna resides at a constant distance of about 30 cm above the surface [70].

12.2.3 *Display*

Typically, the signal that is received by the secondary antenna can be visualized using a standard oscilloscope. Herein, intensity of the reflected signal can be assigned levels of a grayscale, such that internal discontinuities can be visualized. As most equipment, modern GPR devices encompass a number of signal modifications, such as variable gain, filtering or waveform rectification, which significantly enhance signal interpretation.

12.3 *Techniques and Applications*

A number of different approaches have been found most suitable for structural applications, including frequency modulation, synthetic pulse-radar and pulse (impulse) systems. While all of the former methods are applicable to structural inspection, pulsed systems have found greatest practical acceptance and most commercially available equipment [70]. This is in part due to the low power output and consequent elimination of safety concerns, as typically found in systems of higher energy consumption. To adapt systems to dimensions found in structural applications, frequencies ranging from 500 MHz to about 1.5 GHz are most suitable. At 1 GHz, concrete members of 40 cm thickness exhibit the most efficient inspection.

To date, the most widely reported structural applications relate to assessment of concrete bridge decks to detect delamination caused by the uppermost surface of reinforcing steel. Moreover, methods have been developed that identify delamination of asphalt surfacing. Best results are typically obtained for regions within 50 mm from the concrete surface. Moreover, voids and regions of moisture uptake have been located using GPR.

Comprehensive background information on GPR inspection can be found in reports by Lim [69], Bungey and Millard [70], Colla et al. [72] as well as Shaw and Berström [73].

12.4 CAPABILITIES AND LIMITATIONS

The late development of ground radar penetration towards inspection of concrete civil infrastructure has given substantial benefit to rapid localization and quality assessment of defects in concrete components. These include misplacement of reinforcement, severe moisture uptake or discrete air-filled voids. Moreover, inspection via radar enables the user to often de-couple equipment from the structure under inspection, which allows a more rapid inspection process without necessitating time-consuming coupling processes. Nonetheless, a number of significant drawbacks must be emphasized.

Foremost, the principal reported structural applications are related to dimensioning and localizing of major components as well as internal features, such as rebar and air voids [70]. Because relative changes in dielectric constant are a precondition for detectability, accurate sizing of most internal features, including dry air voids and cracks, becomes highly challenging. In addition, features located in close proximity to the surface are difficult to detect. As most transducers are operated in the lower GHz-range, signal reflection off the front surface will occupy a depth of about 100 mm, causing strong interference with signals originating from shallow depths. This imposes a strong limitation to radar inspection of CFRP-rehabilitated components, since most defects are located within a few millimeter of the front surface. Moreover, dictated by the fact that no application of GPR to carbon-epoxy composites can be found in the literature, little is known about the detection-potential of radar in these materials. This may primarily be due to the relatively high conductivity of carbon fibers (i.e. low dielectric constant), which restricts their inspection via radar altogether.

In conclusion, GPR has proven adequate for locating and, within limits, sizing of internal discontinuities of conventional reinforced concrete components. Due to the limited background on applicability to composites, in combination with restrictions imposed by the high conductivity of the material and generally shallow inspection depth, one may conclude that GPR is unfavorable for the inspection of CFRP-rehabilitated concrete members.

13 STRAIN MEASUREMENT TECHNIQUES

13.1 FUNDAMENTALS AND THEORY

Traditionally, surface mounted electrical resistance strain gauges are used in a wide field of applications for monitoring material deformations, both internally and externally. Consisting of a thin electrical wire with predetermined electrical resistance, these gauges are specifically designed to provide highly accurate strain readings (as low as 10^{-6}) while ensuring full strain compatibility with the host material. They are bonded to the test object by means of a thin adhesive film and mostly require protection from the surrounding environment through adequate coatings or covers.

As the base material strains, the thin wire of the gauge is forced to elongate, corresponding to a fixed rise in resistance gradient/unit extension, commonly measured in voltage/microstrain [με]. Although this method remains in wide use for most laboratory testing, it provides only localized information and lacks insight on strain at multiple locations along the entire dimension of a member. In order to provide the user with a more comprehensive strain profile, a high number of individual gauges would be advantageous, though at the expense of an increased logistical effort. For most applications, strain gauges are surface-mounted, while internal applications have mostly been restricted to investigation of rebar in reinforced concrete. Especially due to their relatively high surface area along with demand for protective coatings, electrical resistance strain gauges have not found wide acceptance for use inside laminated composite materials.

Lately, embedded optical fibers have been introduced to overcome the apparent shortcomings of conventional strain gauges. Optical fibers are manufactured from a transparent *core* that is capable of transmitting light waves over large distances. To provide guidance as the light beam, which is emitted from either a broadband diode or laser source, progresses through the fiber, a *cladding* is applied to cover the core surface, thus acting as a reflector. As a result, any portion of the light beam that does not travel parallel to the core axis is reflected at the fiber/cladding interface and forced to continue its path inside the fiber. To permit incorporation of optical fibers in a variety of harsh environments, a protective polyimide coating surrounds the core and cladding, resulting in a total fiber diameter of only about 250 μm in diameter. As such, fibers are significantly smaller than conventional strain gauges and can be embedded into a variety of materials with significantly lower influence on mechanical behavior (Figure 13-1).

The most significant advantage of fiber optics has been brought forward with the introduction of fiber-optic Bragg gratings (FBG). Due to the inherent properties of coherent light, portions of an incident beam traveling though the fiber can be reflected at a grating that essentially acts as a wavelength selective mirror [74]. These gratings are similar to those in optical interferometry (compare Chapter 10) in that they function by means of destructive and constructive interference of coherent light. As the material strains, the grating on the fiber surface is caused to deform, which results in a small change in spatial period. Hence, the frequency content of the reflected signal will shift accordingly. It has been shown that sensors give a linear shift in wavelength in response to linear strain of the Bragg grating, presupposing that strain levels are within the elastic deformation limit of the fibers [74]. This is preferable, since it allows linear correlation between the measured shift in frequency and elongation of the structural component containing the optical fiber.

Because light can be emitted over a large frequency range, previous feature enables the user to apply *multiplexing*, a technique that allows measurement of strain at various locations along a single optical fiber. Essentially, a signal of known frequency content is emitted into the fiber and any signal reflected off a grating is recorded and analyzed. Using a frequency modulated continuous wave signal (FMCW), up to 20 gratings can be included along a single fiber [74]. Since each individual grating can be designed such that is only reflects a specific wavelength and a small derivative thereof, signal frequency content can be easily separated using optical spectrum analyzers (OSA). Subsequently, through known velocity-time relationships, the recorded information can be related to the position of a grating along the fiber.

13.2 INSTRUMENTATION

As for optical methods, a laser source must provide coherent light to send a signal of specified wavelength into the fiber core. A light signal is launched from a broadband source that is responsible for modulating the frequencies. A photodetector is incorporated in the same unit as the laser beam and analyzes the incoming reflected signal of each of the FBG sensors.

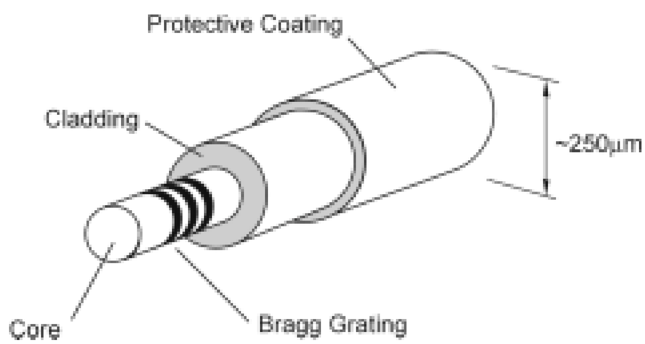


Figure 13-1: Composition of an optical fiber

13.3 TECHNIQUES AND APPLICATIONS

To date, most effort for introduction of fiber optics to civil applications has been focused on new and more comprehensive strain measurement techniques that were formerly difficult to accomplish using conventional electrical resistance strain gauges. Special attention has hereby been paid to investigation of interlaminar fracture behavior of composite materials [74], [75], [76]. Since optical fibers can be fully embedded in the surrounding host material without experiencing significant long-term degradation, their incorporation into the concrete-composite bondline as well composite matrixes has been studied.

Due to the fact that most material anomalies in loaded components yield induction of some form of stress concentration, strain anomalies are likely to be indicative of such defects. Particularly in composite-wrapped concrete components, optical strain gauges have proven to reveal the physical condition change to a greater detail than surface mounted gauges [74]. Herein, both optical and conventional surface mounted gauges were used to monitor the behavior of composite-wrapped concrete cylinders under compressive loading. Results implied that deformation of the concrete core was in most instances larger than that indicated by surface measurements. Also, since the optical fibers were imbedded directly inside the adhesive layer, loss of stress transfer between concrete core and composite layer could be detected at an early stage. However, it was shown that different embedding directions of fibers inside the composite might influence the mechanical properties. As such, largest reduction in flexural strength was observed when fibers were positioned transverse to the load bearing direction.

Chan et al. [75] reported the use of optical strain gages for monitoring of strain development along the concrete composite interface for notched GFRP-strengthened beams in three-point bending. Results showed similar trends as outlined in reference [75] in that strain measured at the interface deviated noticeably from that at the surface. Embedded optical fibers allowed detection of interfacial debonding between the concrete and composite at load levels that were about 20% less than those of visible separation of the two components.

13.4 CAPABILITIES AND LIMITATIONS

Similar to acoustic emission equipment, optical fiber technology allows long-term monitoring of structures with minimal effort, assuming the monitoring system is already incorporated into the design prior to erection of the structure. In rehabilitation, the full potential of optical fibers can be exploited if they are embedded into the concrete-composite bondline to monitor strain distribution and indicate eventual long-term degradation. Unlike most electrical systems, especially those relying on line resistance, optical fibers are immune to interference from electromagnetic or radio frequency related noise [77]. Further, they are extremely small and can thus be incorporated into materials to provide the first ‘smart’ structures. Through multiplexing, the amount of foreign material that is introduced by such a monitoring system can also be greatly reduced.

Despite significant advantages over conventional strain gauges, use of optical fibers in current monitoring remains highly limited. Although a potential alternative to conventional strain gauges, most equipment for optical strain measurements has not yet been fully developed, a factor of particular importance for in-situ applicability. Moreover, the appreciable advantage offered by multiplexing comes at a price. If FBG’s are spaced in too close proximity, *spectral shadowing* can occur, meaning that the recorded signals are not sufficiently spaced apart in order to be separated by the optical receiver. For most experiments, a distance of up to 40 in was required to ensure proper system functionality. Consequently, a considerably long ‘dead-zone’ exists from which no strain information can be extracted, which must be regarded a limiting factor for application of multiplexing in small- to medium scale structures. In addition, if a fiber ruptures during service, the signal of all subsequently placed FBG’s is lost and with it all means of data acquisition [75].

In conclusion, the high potential of optical fibers for detection of material anomalies has not yet been fully investigated or developed. Although it has been shown that the methodology is potentially capable of detecting initiation and progression of stress transfer deficiencies at concrete/composite interfaces, little is known about its potential for flaw detection at stringent service levels. Compared to most manually operated NDE techniques, optical strain measurements lack flexibility since the FBG locations cannot be changed once the fibers have been permanently embedded. As such, the method is highly localized, immobile and does not provide full-field information.

14 MODAL ANALYSIS

14.1 FUNDAMENTALS AND THEORY

In most concrete structures, damage can often be associated with certain forms of material degradation, primarily present in form of moisture absorption, excessive spalling, concrete cracking and corrosion of internal steel reinforcement. As a result of the consequent change in material properties, mass and stiffness of a structure are likely to be altered as well. Hence, it can be assumed that, as a structure undergoes certain forms of degradation, its vibration characteristics will change.

For many years, modal analysis has been used to investigate vibration characteristics of mechanical components, including aerospace components and rotational machinery. Lately, the field of modal testing has been extended towards testing of existing structures to comment on serviceability and loss in performance through eventual degradation of individual components [78], [79], [80]. As mentioned above, a gradual change in material performance, promoted by the progression of above-mentioned factors, will most likely result in changes of the variation characteristics. Herein, modal frequencies, mode shapes and damping properties of structural components, such as bridge superstructures, are of paramount interest. These can be extracted through modal testing, which has proven suitable for in-situ testing of structures, even on the large scale. In the following, the methodology employed in modal testing will be outlined and discussed.

To excite a structure for modal measurements, two methods of excitation can be chosen, namely input-output (*active excitation*) and output only (*ambient noise*). Input-output methods of excitation involve a contact procedure in which a forcing function is introduced to initiate vibration of the structure. Typical forms of excitation entail impact hammers, drop weights, shakers or displacement-release. As may be noted from the previous examples, waveforms used in modal analysis can be of various natures, including harmonic and random input, as well as impulsive excitation [78]. Output only excitation is present as long as the structure is in service and under some form of external excitation, e.g. vehicular traffic or wind loads [81], [82]. In field testing, dynamic properties are extracted by placing a number of motion sensors at predetermined locations along the structure. To suit the need for full-motion recording, triaxial accelerometers are commonly given preference [78]. The objective of placing sensors in multiple locations is to attain sufficient amount of frequency response functions (FRF), such that individual modes can be identified from the modal test. Herein, the highest measurable mode depends largely on optimal placement of accelerometers, i.e. extraction of higher modes demands a higher number of accelerometers. As the structure is excited, acceleration data is streamed to a recording device where the frequency response functions are stored. Following computational analysis, which is commonly performed by software incorporated in laptops, frequency and damping ratios for each mode of interest can be calculated. A schematic of the general modal testing field examination is depicted in Figure 14-1. The illustration shows vibratory motion of a two-span bridge superstructure in its first mode of longitudinal bending (Mode I).

As previously discussed, damage/deterioration of structural components can be related to changes in dynamic properties [79]. Hence, to comment on probable deterioration of structural components, vibration properties must be monitored in successive intervals and compared to properties of the initially sound structure. Given the fact that most structures were erected prior to implementation of modal analysis into civil testing methodologies, an experimental baseline of dynamic properties, i.e. vibration behavior of the sound, undamaged structure is often not made available to engineers. Instead, finite element models are commonly utilized to mimic the vibration properties to such detail that the model can be assumed representative of the original structure. By successively comparing the FEM baseline model with data extracted from field experiments, engineers are given means to comment on overall performance of the structure.

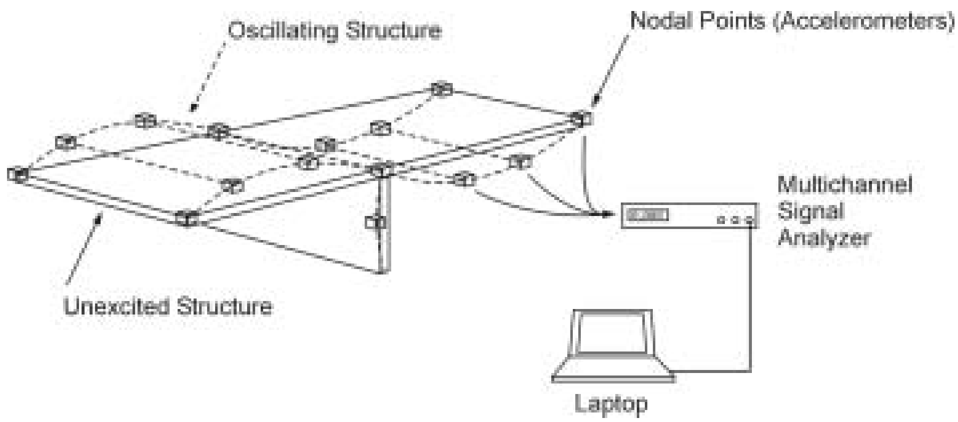


Figure 14-1: Modal testing of large-scale structural components

14.2 INSTRUMENTATION

For active excitation, modal analysis systems are typically comprised of a single excitation mechanism, a multitude of individual transducers, which acquire the parameters of interest, as well as an analyzer to extract the desired frequency response information [83]. Data from the accelerometers is collected and processed by multi-channel signal analyzers, from where it can be conveniently transferred to PC's or laptops for further analysis. In passive excitation, ambient vibration serves as a substitute for the loading mechanism and is hence not necessitated. Apart from portability restrictions set forth by massive impact devices, modal analysis equipment is typically located in compact units, which serve towards increased mobility as well as protection from harsh environmental influences.

14.2.1 EXCITATION SOURCES

In order to record data and information about the vibration characteristics of a structure, an excitation mechanism is necessary. For input-output excitation, several different systems are available, including impact hammers, drop weight impactors or shakers. Since no single method is superior to another, preference is dependent on individual site conditions and consent of the tester. Important in choice of impact equipment is the magnitude of the weight, since this is the governing factor for producing acceptable signal-to-noise ratios [78]. Also, size of and accessibility to the structure are of importance as they largely influence the weight and portability of the exciter. Alternative to force-excitation, the structure may be excited by means of displacement-release. However, this method is often difficult to realize in the field. Moreover, it was shown that it might possibly limit the range of available modes for extraction [81]. Some of the most common excitation sources employed in modal testing are shown in *Figure 14-2*.

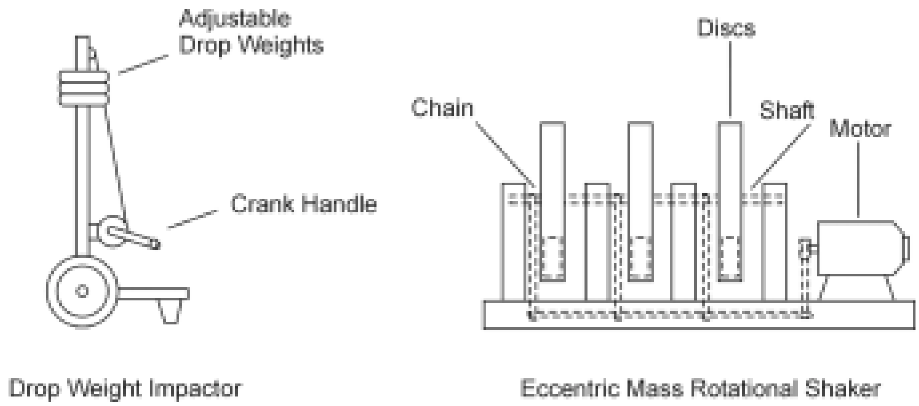


Figure 14-2: Various excitation sources

14.2.2 TRANSDUCERS

Among the various types of transducer, the piezoelectric type is typically given preference in modal testing [83]. Depending on the desired quantity measured, two inherently different types of transducers can be used in modal testing namely force transducers and accelerometers. In former type, force from an external vibration is transferred through a casing directly into the piezoelectric crystal, which then generates an electric charge corresponding to the magnitude of deflection. Because the force must be transferred through the casing into which the crystal is installed, cross-sensitivity from shear of transverse loading represents a source for erroneous readings. Accelerometers utilize a slightly different configuration in which the piezoelectric crystal is located between the casing and an additional seismic mass, acting as an inertia force. Thus, within a certain frequency range, the transducer records acceleration of the body it is attached to. In this type of configuration, the lowest resonant frequency of the transducer is of particular interest, since this defines the working range of an accelerometer [83]. Figure 14-3 shows an example of a typical accelerometer, which are most commonly used for modal testing of large structures.

14.2.3 DATA PROCESSING

As the structure undergoes vibration, data continuously streams from each of the various accelerometers into a central signal-analyzing unit (Figure 14-4). Upon acquiring an adequate number of excitations of acceptable signal level, this data is transferred to a stationary or portable computer that extracts the damped natural frequency and damping ratios for each of the individual modes of the structure. Depending on the number of accelerometer points, the individual modeshapes can be displayed to a greater detail. Utilization of a high number of transducers is particularly important if one seeks to extract higher modes of vibration, as these contain a much larger number of nodes.

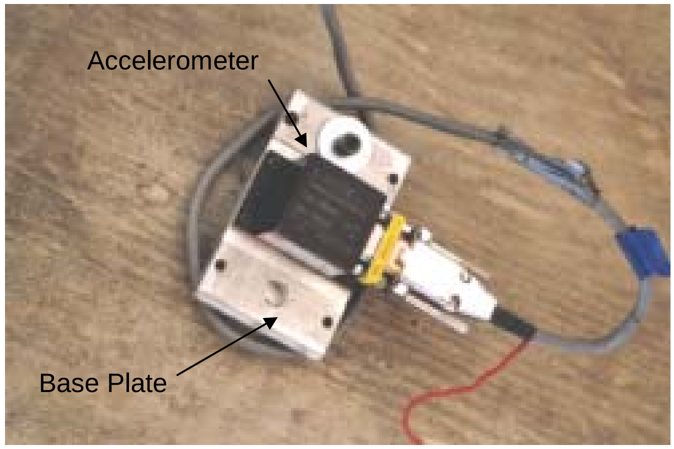


Figure 14-3: Piezoelectric transducer on base plate

Figure 14-4: Portable acquisition unit

14.3 TECHNIQUES AND APPLICATIONS

Driven by the continuous deterioration of today's civil infrastructure, modal analysis has already attracted considerable attention as a mean for monitoring and characterizing onset and progression of global structural damage [78], [80]. Consequently, this has led to the development of methodologies for stationary and in-situ documentation of changes in modal parameters of structures, some of which can be found in [78], [79], [80], [84]. Whilst mostly applied to measure levels of deterioration in conventional reinforced concrete structures, recent projects were aimed towards investigating the efficiency of CFRP-rehabilitation schemes. Herein, it was assumed that the global stiffening, induced by the external bonding of pultruded CFRP strips or in-situ-processed composites, would yield changes in modal characteristic that can be extracted from such tests.

In the civil sector, modal analysis has found highest acceptance in investigation of long-term deterioration, i.e. loss in structural performance of medium- to large-scale structures. Often, these structures already display a significant degree of visible damage, such as flexural and transverse cracking along with consequent discoloration caused by corrosion of internal steel reinforcement. The general test methodology employed in modal analysis is large structures is discussed by Bolton et al. [78]. Herein, they investigated a concrete box-girder overcrossing consisting of two spans, each of about 120 ft in length. The entire structure was modeled using a total of 30 nodal response points, yielding an average spacing between transducers of approximately 20 ft. Modal test data was collected incrementally in several data sets using a portable instrumentation setup consisting of five to seven individual accelerometers. The test employed an impact hammer with variable tip weight as to adjust for the needed impulse levels that were required to excite the structure and develop acceptable signal-to-noise ratios. The resulting excitation pulse contained frequencies of 100 Hz or less with duration of approximately 10 to 15 milliseconds, causing acceleration extremes ranging from 0.003 to about 0.025g. System sensitivity is typically adequate to sense these levels of excitation. To comment on eventual deterioration of the structure, two 3-day modal field tests were performed at an interval of roughly one year. Surprisingly, modal parameters extracted from the second field test yielded an increase in modal frequency, i.e. a stiffening of the structure, which is contradictory to the expected decrease in modal frequency. These unexpected changes were attributed to differences in environmental conditions, as the first test was performed under moist conditions, yielding a higher structural mass and consequently lower modal frequency.

14.4 Capabilities and Limitations

Traditionally, modal analysis has been used to analyze damage in small- and medium scale components, most of which show high material homogeneity and clearly defined boundary conditions. Unlike these former approaches, modal analysis of civil structures brings upon new and challenging difficulties, mainly due to the unusually high material-variability, environmental instability and procedural variations related to collection, extraction and interpretation of in-situ data streams. Herein, unknown boundary conditions of large-scale structures, promoted by presence of considerable deterioration near abutments, as well as the large environmental fluctuations may be considered predominant factors. Quite often, these factors contribute towards high variability and sometimes inconclusive test results. As previous research has shown, variations in the structural mass, given as a result of moisture uptake, can result in significant signal scatter between successive field tests [78]. This, in turn, may lead to erroneous interpretations, such as loss in stiffness and consequent internal structural damage.

In view of the present discussion, modal analysis presents further drawbacks. Foremost, one should critically assess the maximum obtainable sensitivity of modal testing of large structural components. On structures often exceeding several hundred feet, it may be concluded that signals generated at discontinuities in or below the CFRP material are of insignificant size to contribute to the overall modal response. Moreover, an almost infinite number of internal discontinuities inherent to the concrete substrate (moisture, voids, internal reinforcement) will contribute to background noise, most likely resulting in a shadowing of any such signal.

Apart from former sensitivity-related aspects, the user is confronted with a variety of practical concerns, as subsequently discussed. Firstly, modal analysis entails considerable limitations in terms of real-time data acquisition capability. Although the data stream is collected and permanently stored in the field, analysis as well as the rather complex interpretation of the collected waveforms must often be performed off-site. Hence, no instantaneous assessment can be given on the current state of structural integrity. Secondly, identification of changes in modal response necessitates precise knowledge of a baseline model, which can only be provided through complex FEM analysis. Alternatively, the relative change in modal response may be obtained from two or more successive field tests, which imposes a significant time delay, as one may not draw any conclusion on structural integrity until after conclusion of the second test.

Given the above, it remains doubtful whether modal data can display changes in vibration characteristics to such high detail that is allows the inspector to comment on changes in quality of externally bonded rehabilitation schemes, particularly in situations where these are of highly localized occurrence. Hence, it is concluded that modal analysis remains a tool of global structural analysis, which shows little feasibility for detection of localized damage in externally bonded CFRP composites.

15 RAPID LOAD TESTING

15.1 Fundamentals and Theory

Prior to erection, structures are designed based on certain predefined maximum permissible levels of loading and deflection. A structure is considered to be in good or serviceable condition as long as these limiting criteria are not exceeded under service load levels. With progressing age, individual components are likely to experience distinct forms of material degradation, such as fatigue cracking, moisture absorption or creep, directly affecting the overall performance of the structural system they are integrated into. In most cases, material degradation can be linked to a reduction in stiffness [78], hence members will become more flexible once they show significant levels of one of the above degradations or a combination thereof. Since load-deflection behavior of individual members, such as transverse girders, can be directly related to their stiffness, one may conclude that a component, which shows sufficient levels of degradation, is likely to exceed its preset levels of deflection. In a general sense, the principle of rapid load testing is based on this methodology.

Often, material composition and geometry are not known to a sufficient degree, which restricts the feasibility of analytical approaches and necessitates the use of alternative methodologies. One such methodology is given by the rather simplistic approach of applying an experimental loading condition that, within limits, simulates the real-life situation given at a distinct location within the structural system. Thus, experimental testing can provide a more representative and meaningful evaluation of the structure.

Although modeling of most real-life loading conditions requires replication of a uniform downward pressure, loads are mainly induced at a single point and the corresponding deflections are measured at various locations along the member. Herein, loads are commonly applied via hydraulic jacks in combination with a load cell to monitor the applied levels of loading. For any given structure, the critical load levels are typically defined as 85% of its factored design load, excluding any loads induced by self-weight or test equipment [85]. At numerous locations, linear variable differential transformers (LVDT) serve for deflection measurement. Apart from deflection, material strain, crack growth and rotation are commonly also of interest. These parameters can be instrumented via use of electrical resistance strain gauges, extensometers and inclinometers, respectively.

Depending on load magnitude and specific test conditions, a suitable test setup must be chosen. To complement testing at both ground- and elevated levels, a number of different load application methods are typically utilized. Because high levels of loading are induced at an isolated location, reaction forces must be directed into a multitude of suitable supports, which can be provided in form of other members, situated in close vicinity to the test member, or through ground fixation by means of steel chains. Regardless of force transfer mechanism, distribution of the induced hydraulic reaction force is paramount as it reduces the risk of failure in secondary components of the structure. Illustrations of some of the most frequently employed loading schemes are depicted in Figure 15-1.

In early load testing procedures, loads were applied statically for about 24 hours after which the first deflection reading was taken. A second measurement followed roughly 24 hours subsequent to removal of the load to supply information on deflection recovery

capability of the structure. In rapid load testing, duration can be significantly shorter, while its cyclic nature is considered a suitable substitute for the 24-hour sustained load of earlier applications [85].
Similar to modal testing, the principle of defect detection in rapid load testing is manifested by a stiffness reduction principle. Herein, it is assumed that a sound structural component retains its initial stiffness as long as no material deficiencies are introduced. With the onset of material degradation, stiffness is likely to be reduced. As a result, one may conclude material degradation simply based on increase of deflection under identical levels of externally applied load. However, this presumes that such variations are of sufficient magnitude to be sensed by the load testing system. Thus, if defects develop or progress in locations of structural irrelevance, they are likely to go undetected.

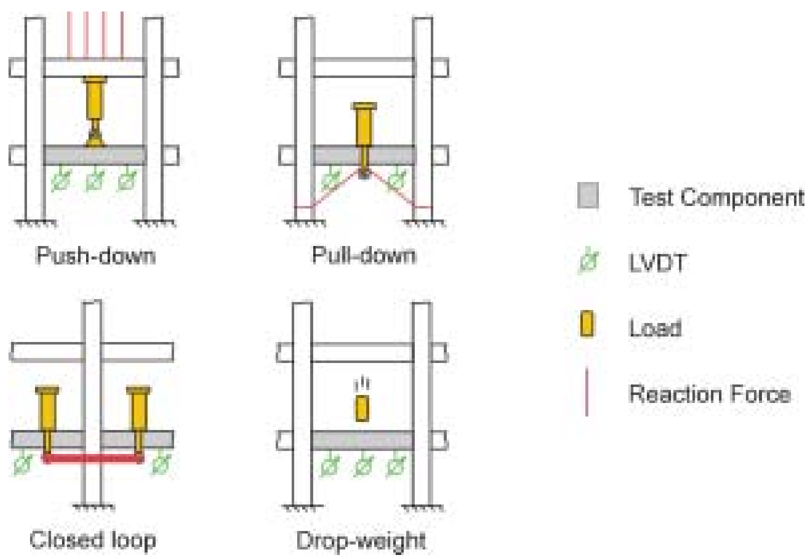


Figure 15-1: Common loading-mechanisms in Rapid Load Testing [85]

15.2 INSTRUMENTATION

Systems for rapid load testing are similar to those utilized for structural testing in many laboratories. Complete systems encompass one or several hydraulic actuators, typically capable of developing extremely high loads. Such high capabilities are required to complement the forces required to induce noticeable deflections in structural members. To monitor the corresponding deflection of the member under investigation, a number of deflection, rotation and strain measurement devices are used. Lastly, data acquisition systems store all information provided by actuator and measuring devices.

15.2.1 HYDRAULIC ACTUATOR AND PUMP

Hydraulic systems provide efficient means to develop the usually high forces required in load testing. A typical system is comprised of a pump, controlling the flow of hydraulic oil, as well as a telescopic actuator (Figure 15-2). Both components are connected by two pressure hoses that allow hydraulic oil to flow to and from the piston inside the actuator. Pressure regulators allow exact control of oil flow, such that load can be increased and decreased at a desired rate. A load cell is typically installed between the actuator and component to allow continuous monitoring of the applied force.

Figure 15-2: Hydraulic jacks

15.2.2 Measuring Devices

Deflection measurements are commonly performed by use of highly sensitive devices, such as strain gauges or extensometers. As mentioned earlier, electrical resistance strain gauges provide sensitivities as low as 1 με, whereas the recommended minimum measurable value of extensometers lies at about 50 με [85]. While strain gauges find use mostly for monitoring of crack growth phenomenon, LVDT's provide sufficient sensitivity for most load-testing applications. Due to their small dimensions, they often require a supporting fixture, such as a tripod, to be located at elevated height. With increasing deformation of the extensometer shaft, an electronic signal is delivered to a data acquisition unit for recording and further evaluation.

15.2.3 Data Acquisition

To perform measurements at various locations throughout a structure, a large number of strain- and deflection devices are required. This implies that the recording system must supply adequate capabilities to complement the incoming data stream. Since each device occupies a separate channel for data storage, large data acquisition bays (Figure 15-3) are commonly used. From there, data is swept onto computers for permanent storage and evaluation.

15.3 Techniques and Applications

Numerous case studies and commercial projects have been conducted, which are discussed in great detail by Mettemeyer and Nanni [85]. Most tests were aimed at evaluation of concrete structures that had undergone external strengthening by means of bonded steel- and CFRP plates. Since the use of CFRP for external strengthening of structures has not yet been accepted as a standard practice, rapid load testing has been used to validate and 'proof' test their performance.

According to the methods outlined in Section 15.1, loads were applied in various locations, including pushdown, closed loop, vehicle, and dropped weight. In testing of individual rehabilitated components, loads were limited to levels not exceeding 85% of the factored design moments, which resulted in a linear response for all load levels and configurations. In all cases, a stiffening effect of the strengthened member could be observed.

Figure 15-3: Multi-channel data acquisition bay

15.4 CAPABILITIES AND LIMITATIONS

Rapid load testing has proven to be a useful tool in evaluation of post-strengthened structural components [85]. Based on variation in stiffness (and consequently deflection) under cyclic loading, efficacy of the rehabilitation method can be assessed. If the induced loads are limited in such ways that they do not exceed a linear load-deflection range, the method can be assumed to be of non-destructive nature without causing reduction in performance to the individual members or the structure as a whole. Because much of the equipment utilized in rapid load testing is commercially available and currently employed in many structural-testing facilities, familiarity with equipment and methodology of the technique can be presupposed.

Problems for non-destructive evaluation, especially on a local scale, can arise insofar that the system is highly capable of capturing a multitude of local effects and combining them into a single response, while the individual initiators may not be clearly distinguishable. Such local initiators include, but are not limited to, concrete cracking, debonding at concrete-composite interface, fiber rupture, and moisture absorption. As such, a distinct separation between the individual defects, assuming a noted reduction in stiffness, becomes virtually impossible. Also, the true non-destructive characteristics of rapid load testing may be limited to a level at which defects in composites have already exceeded acceptable limits. In other words, defects in CFRP composites or interfacial regions between CFRP and concrete may not be of sufficient magnitude to alter the load-deflection response acquired during a rapid load testing procedure. Currently, this area has not been investigated and thus remains subject to further research.

Summarized, the method is likely to lack sensitivity to small defects as well as the capability to provide characterization in terms of size, location and magnitude of individual flaws. Hence, in comparison to most of the previously discussed NDE methods, rapid load testing shows severe limitations for defect detection in CFRP strengthening systems.

16 DISCUSSION AND CLASSIFICATION

16.1 INTRODUCTION OF A CLASSIFICATION METHODOLOGY

Hitherto, the reader has been given a general review of NDT techniques as well as a number of data-collection methods, most of which have already been implemented into industrial inspection procedures or are currently used for numerous experimental research applications. The individual techniques have been discussed in terms of basic methodology, instrumentation, recent applications, as well as capabilities and limitations. It was shown that successful application of techniques is largely dependent on a variety of test parameters, such as material composition, dimension and surface texture of the test object, as well as test conditions and means of data acquisition/interpretation. Hence, to comment on applicability of individual NDT methods in view of the present discussion, former characteristics of such methods must be reviewed and classified with special consideration of their applicability to CFRP-rehabilitated structural components.

As mentioned, a limited body of work discussing NDT of CFRP-rehabilitated components has been made available. Whilst serving strongly in assessing the suitability of a few established NDT techniques, most traditional and late methods cannot dispose of such background and must thus be classified on an alternative basis. Primarily, techniques that have proven to be applicable for investigating CFRP must be rated higher than those having little to no history in nondestructive evaluation of composites. As mentioned earlier, a suitable method must satisfy two preconditions, namely:

- Possess characteristics that strongly encourage its use on CFRP overlays, i.e. provide adequate detectability, preferably supported by previous research conducted in the composites sector
- Utilize equipment which meets the practical necessities imposed by in-situ NDT, i.e. be suitable for inspecting a variety of geometric configurations and be operable in a number of different field environments

In review, defect detectability entails system sensitivity, transparency, and reproducibility, all being factors of paramount importance. Conversely, practical aspects are related to portability, system complexity, flexibility, as well as equipment availability and cost. Herein, it is imperative that the individual requirements be given relative levels of importance.

Foremost, non-destructive testing techniques must allow the inspector to obtain information from inside the composite material or concrete/composite interfacial regions to such detail that predictions on the overall integrity of the composite/concrete system can be made. While this does not imply a global assessment on structural safety, defect type, -location, and –size should be obtainable from a potential technique. Although practical aspects can have a profound effect on efficiency, safety, as well as equipment- and labor expenses, only systems yielding high detectability can be considered feasible. Undoubtedly, methods not capable of providing the desired level of sensitivity and comprehensiveness are to be disregarded, unconditional of their practical merits. Hence, compared to practical aspects, defect detectability will generally be assigned a higher level of importance. Nonetheless, if stringent safety requirements or unjustifiably high cost imply practical limitations, the former ranking scheme shall be revised and adjusted accordingly. However, stringent practical limitations will not result in immediate exclusion of the method as in the case of insufficient detectability. Figure 16-1 depicts the individual steps of the previous ranking rationale in more detail. Although adherence to the ranking procedure should not be considered stringent in every aspect, it provides insight to the general rationale.

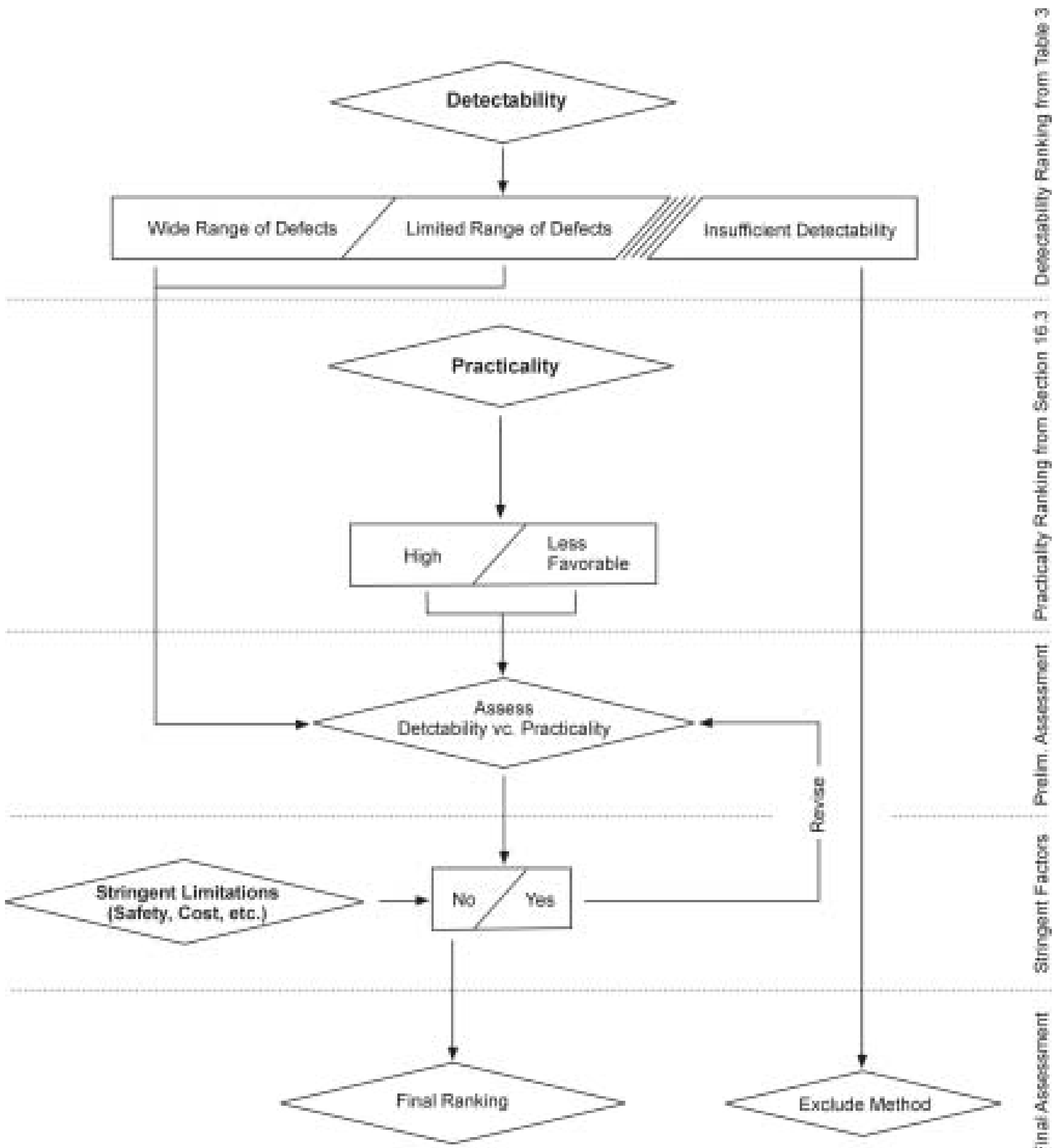


Figure 16-1: Flowchart for ranking assessment

As may be seen, Figure 16-1 entails information given in Table 3 as well as individual graphs of Table 4 to comment on detectability and practicality, respectively. In the following, the rationale for obtaining this information will be presented. Because detectability and practicality each encompass a number of subcomponents, which can be of considerable relevance for an individual technique, these will be discussed in further detail. Components of the classification scheme include the following:

1. Defect Detectability
   - Range of detectable defect types
   - Minimum detectable defect size
   - Range of detection depth

2. Practicality
   - System type [near-field/full-field/global]
   - System portability
   - Coupling requirements
   - Real-time data acquisition
   - Ease of interpretation
   - Possible service inflictions
   - Initial and servicing cost of equipment
   - Level of sophistication

Ideally, it would be preferable to obtain defect detectability from a number of field- or laboratory experiments. However, for most techniques, such information has not yet been made available. Moreover, presence of a concrete substrate can cause substantial signal interference in form of scattering or absorption. Due to this limited knowledge, the classification matrix shown in Table 3 must, at present, be considered mostly qualitative. Although minimum detectable size and depth penetration will later be of profound importance, it is extremely difficult to assess at this point.

16.2 DETECTABILITY MATRIX

The detectability matrix (DM) is given in Table 3. Only a limited number of defects were chosen for assessment purposes, most of which can be considered to be of likely occurrence in laminated composite materials. Those omitted are mostly related specifically to CFRP-rehabilitation, e.g. high spots, substrate degradation, etc., and hence cannot be assessed at this point. Further, the reader should differentiate sharply between defects that cannot be identified (⇩) and those of which detectability is currently unknown (-). The DM differentiates between *unknown* and *unidentifiable* in such manner that former does not necessarily imply unsuitability of a method towards the specific type of defect. Rather, the method has not yet been investigated upon its sensitivity to this type of defect, hence no assessment can be given. Contrary, unidentifiable defects are those for which insensitivity has already been proven. Furthermore, capability of localizing and sizing of a specific form of defect is addressed.

Table 3: Detectability Classification Matrix

NDE METHODS	DEFECT TYPES							
	Delamination	Voids	Moisture	Resin Thickness Irregularities	Fiber Waviness	Fiber Breakage	Porosity	Matrix Cracking
Visual Testing (VT)	⇨$_{L}$	⇩	⇩	⇩	⇨$_{L,S}$	⇩	⇩	⇩
Acoustic Impact Testing (AIT)	⇧$_{L}$	⇨$_{L}$	⇩	⇩	⇨$_{L}$	⇨$_{L}$	⇩	⇩
Penetrant Testing (PT)	⇩	⇩	⇩	⇩	⇩	⇨$_{L,S}$	⇩	⇨$_{L,S}$
Ultrasonics (UT)	⇧$_{L,S}$	⇨$_{L}$	⇨$_{L}$	-	-	⇩	⇩	⇩
Radiographic Testing (RT)	⇧$_{L,S}$	⇧$_{L,S}$	⇨$_{L,S}$	⇧$_{L,S}$	⇧$_{L,S}$	⇧$_{L,S}$	⇧$_{L,S}$	⇧$_{L,S}$
Thermographic Testing (TIR)	⇧$_{L,S}$	⇨$_{L,S}$	⇨$_{L}$	-	-	-	-	⇩
Eddy Current Testing (ET)	⇩	⇩	-	⇩	⇧$_{L}$	⇧$_{L}$	⇩	⇩
Optical Methods (Shearography)	⇧$_{L,S}$	⇧$_{L,S}$	-	-	⇧$_{L,S}$	⇧$_{L,S}$	-	-
Acoustic Emission (AE)	⇨	⇩	⇩	⇩	⇩	⇧	⇩	⇧
Ground Penetrating Radar (GPR)	-	-	-	-	-	-	-	-
Strain Measurement Techniques (Optical Fibers)	⇨$_{L}$	⇩	⇩	⇨$_{L}$	⇨$_{L}$	⇩	⇩	⇩
Modal Analysis	-	-	-	⇩	⇩	-	⇩	⇩
Rapid Load Testing	-	-	-	⇩	-	-	⇩	⇩

⇧ Generally Detectable ⇨ Limited Detectability ⇩ Not Detectable - Detectability Unknown

Indices: L = Allows localization
S = Allows accurate sizing

Note: Microwave Testing has been omitted from this table as its general methodology has been outlined through discussing ground-penetrating radar (GPR) in Chapter 12.

As may be noted, capability of techniques to detect presence of defects does not necessarily imply the ability of localization and sizing. Excellent examples of this are acoustic emission as well as optical fiber measurements. Although signals of internal material fracture and/or friction can be sensed by both methods, exact localization and sizing, former being especially critical for AE, pose extreme difficulties. As was discussed, the material anisotropy of CFRP yields localization via AE measurements even more inconclusive. Hence, only methods bearing indices 'L' and 'S' show adequate means of defect characterization.

16.3 PRACTICALITY MATRICES

Irrespective of previous application to CFRP-rehabilitated structural components, most of the above methods have found use in one or multiple fields of engineering. Hence, much information can be given on equipment and overall system complexity, as well as the detection methodology of each individual technique. Although practicality entails a number of individual aspects, experience gained through past applications often provides the eventual difficulties in system setup, data acquisition, interpretation, portability issues, etc. Such background knowledge thus builds the basis for subsequent practicality assessment.

A template for the practicality matrix (PM) is shown in Figure 16-2. To aid the reader in comparing individual methods, the matrix displays information in graphical format. As may be seen, individual aspects are assigned columns of various heights, with longer columns representing a more preferable situation while implicit limitation are indicated by a short column height. This appears particularly helpful since the overall practicality must be considered a combination of its individual components. Hence, from comparing the overall column heights, one may quickly discern unsuitable methods from those yielding high practicality.

Also, the PM includes a short list of some of the most outstanding advantages and/or disadvantages of each individual method. Similar to the detectability matrix, three distinct levels of practicality are used in the ranking scheme. It should be noted that certain parameters cannot be ranked and are thus classified as 'not applicable'. In cases where one method may be applied in different forms (e.g. A-scan versus C-scan) dotted lines are used to indicate a range of practicality variation. In such cases, a footnote will provide further information of why such variability must be granted. In the following, a brief introduction to each of the individual practicality parameters is given.

16.3.1 SYSTEM TYPE

Foremost, NDE systems can be assigned to one of three general system types, namely near-field, full-field and global. The profound difference between these system types is given by their field-of-view. As such, a global system is preferably used to obtain information on a structural level, while near- and full-field techniques serve a more localized and detailed analysis in regions where presence of defects is known or expected to be of particularly high occurrence. While global methods can provide rapid insight to large discontinuities and overall structural deficiency, they typically lack sensitivity to localized defects. Conversely, local systems are given preference once defects have already been located on a global level, as they provide enhanced sensitivity to minute anomalies. As discussed, a suitable combination of the two can provide means for rapid inspection on the structural level with subsequent near-field capabilities for a more detailed inspection.

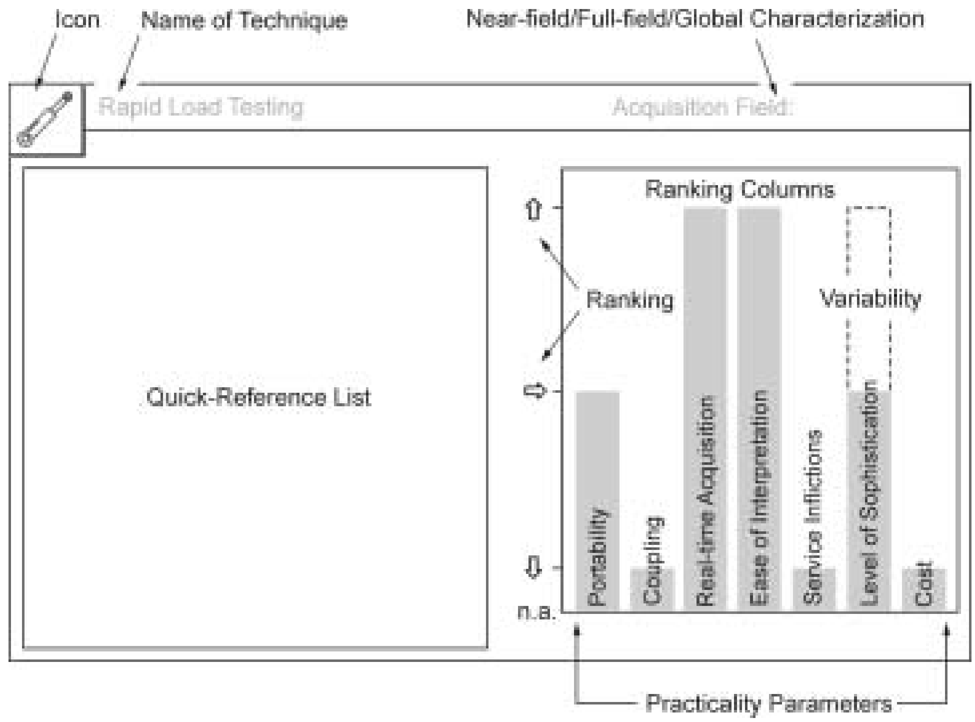


Figure 16-2: Practicality Matrix

16.3.2 PORTABILITY

As for all field inspection, portability and ease of handling of test equipment and related tooling is of paramount importance. During local inspection, equipment must be easily transportable from one location to the next, preferably by a single person. Quite often, bulky equipment restricts applicability of a technique simply because inspectors cannot handle, adjust or even assemble the individual components in the field. For global methods, which may allow users to inspect entire parts of a structure from a single location, portability, as outlined above, will be of less significance. Nevertheless, global methods must be portable insofar that equipment is of manageable size and weight to be transported to and from the site. Generally, portability of global testing equipment entails any factors restricting the removal from a laboratory environment, such as high power source, environmental sensitivity, etc.

16.3.3 COUPLING

Intimate contact requirements can impose great limitations on the overall efficiency of an NDE method. The necessity to provide permanent coupling between the part and inspection tool often results in a slow and sometimes messy inspection procedure, especially in cases where gels or chemicals are applied to the test surface. Further immediate- and long-term effects of couplants and chemicals on the integrity of CFRP laminates have not yet been established. Thus, to ensure a more efficient scanning process, it is preferable to operate all equipment in a non-coupled arrangement, i.e. data can be acquired without intimate contact to the structure.

16.3.4 Real-time Acquisition

To allow in-situ interpretation, data acquisition shall be realizable in real-time, i.e. inspection must be performable as to extract all information during or directly following completion of a testing cycle. Herein, difficulties typically arise in cases where a method requires massive computational effort or development of exposed films in a laboratory environment. In most cases, the use of digital systems in combination with modern laptop computers can facilitate faster acquisition times as well as more efficient computation process.

16.3.5 Ease of Interpretation

Upon completion of the acquisition process, the user is typically presented a plot or image, showing a systematic representation of the collected data in a tabular, graphical, or other suitable format. Ideally, graphical images show the inspected part in two-dimensional view with information superimposed in the desired format (e.g. temperature contours in IR testing, strain profiles in shearography, etc.). These ‘mapped’ images are most convenient to interpret as the observer can best correlate between the displayed image and test part. Contrary, information provided in x-y coordinate systems (e.g. A-scan, AIT force-time history plot) are more difficult to interpret and require a more fundamental knowledge of the technique.

16.3.6 Service Inflictions

During inspection, serviceability of the structure should not be influenced to a significant degree, i.e. inspection teams should not be required to disrupt traffic or shut down entire lanes of a bridge. Typically, infliction with traffic is required due to one of two reasons. Firstly, the test setup may require simultaneous access to one or multiple traffic lanes, such that inspectors would be exposed to a significant safety hazard if traffic was not disrupted. Secondly, ongoing traffic may induce vibration to the structure that, while preferable for passive methods, may result in background noise and/or erroneous readings for a number of active methods. Hence, methods that are immune to either of the two formerly mentioned conditions are most preferable.

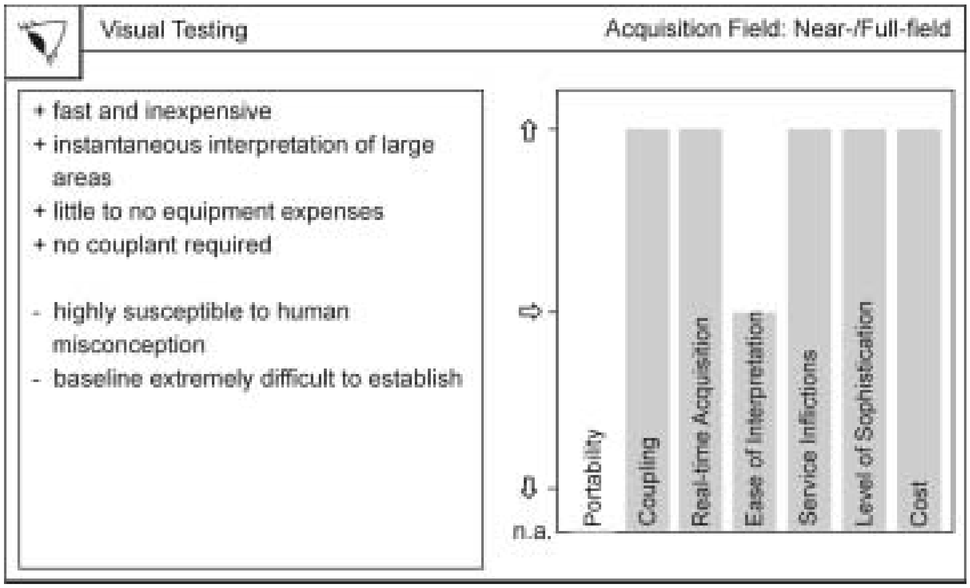
16.3.7 Level of Sophistication

Sophistication is mainly dictated by the amount of previous research and practical work conducted in a specific area. Although a method can be rather simplistic, a long history of industrial and experimental application ensures familiarity, reproducibility and higher efficiency during inspection. Further, equipment is likely to be more readily available and obtainable at lower cost. As such, sophistication is profoundly different from the level of complexity, which mostly relates to how exhaustive and detailed the given information is. However, high complexity does not necessarily imply a high level of industrial establishment.

16.3.8 COST

Equipment cost is mostly regulated by two factors, namely complexity and industrial widespread. In most instances, complexity may be assumed to be the governing factor, however, high industrial demand often leads to a significant reduction of equipment and instrumentation cost.

Table 4: Practicality Matrices



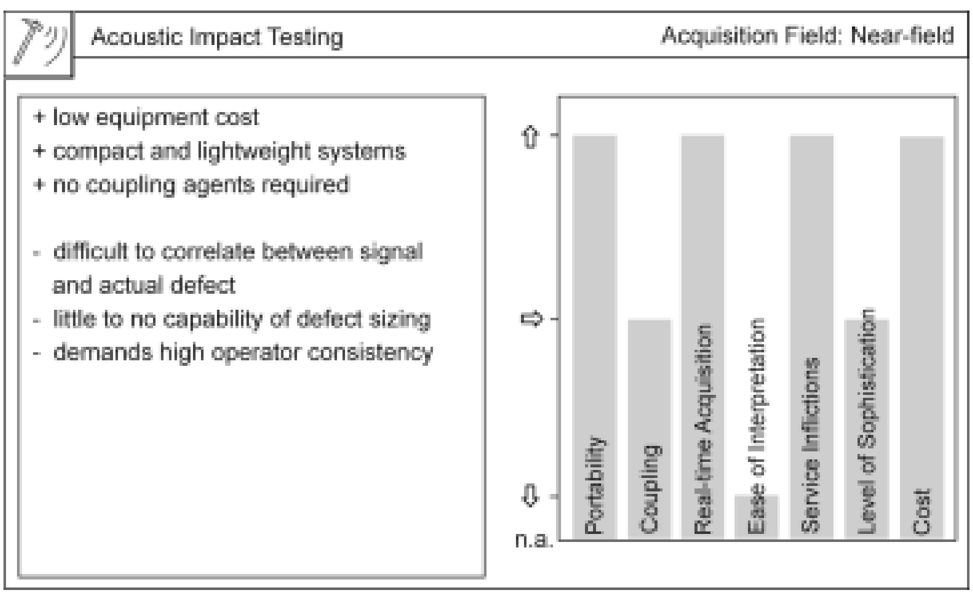
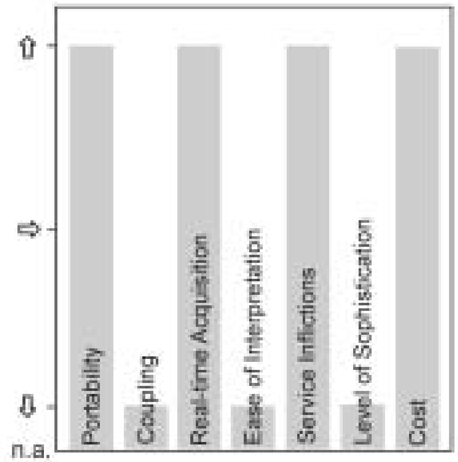


Table 4: Practicality Matrices (continued)

Penetrant Methods — Acquisition Field: Near-field

+ low material cost
+ equipment readily available as 'kit'

- illumination and interpretation difficult under in-situ conditions
- use of chemicals with widely unknown compatibility
- little to no past experience in use on fiber composite materials



Ultrasonics — Acquisition Field: Near-field

+ applied extensively in research and industry
+ highly sophisticated equipment at relatively low cost
+ high mobility (A-scan, B-scan)

- continuous coupling required
- difficult to apply on rough/uneven surfaces
- 'mapping' only available on C-scan

Comments:
Ease of interpretation varies significantly, depending on the type of system used. An inverse relationship between interpretation and equipment cost exists, i.e. expensive units are capable of providing more conclusive images

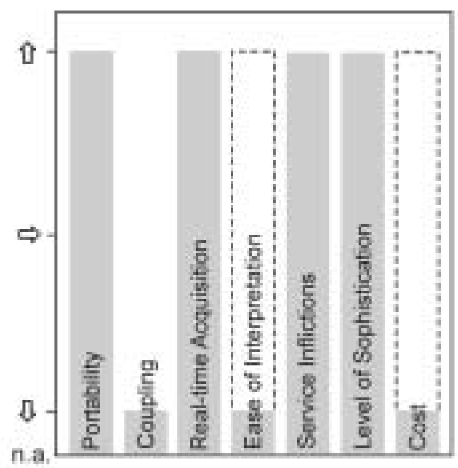
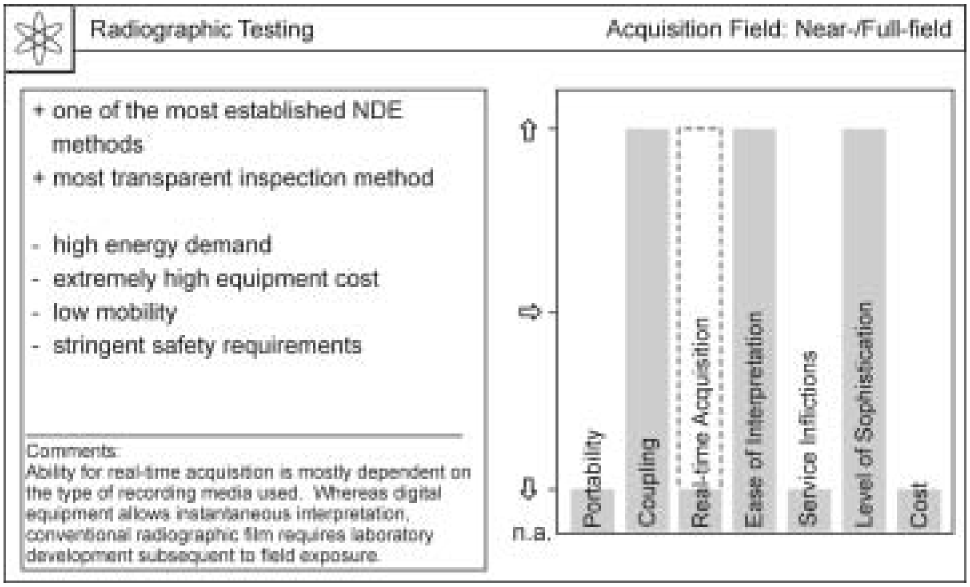


Table 4: Practicality Matrices (continued)



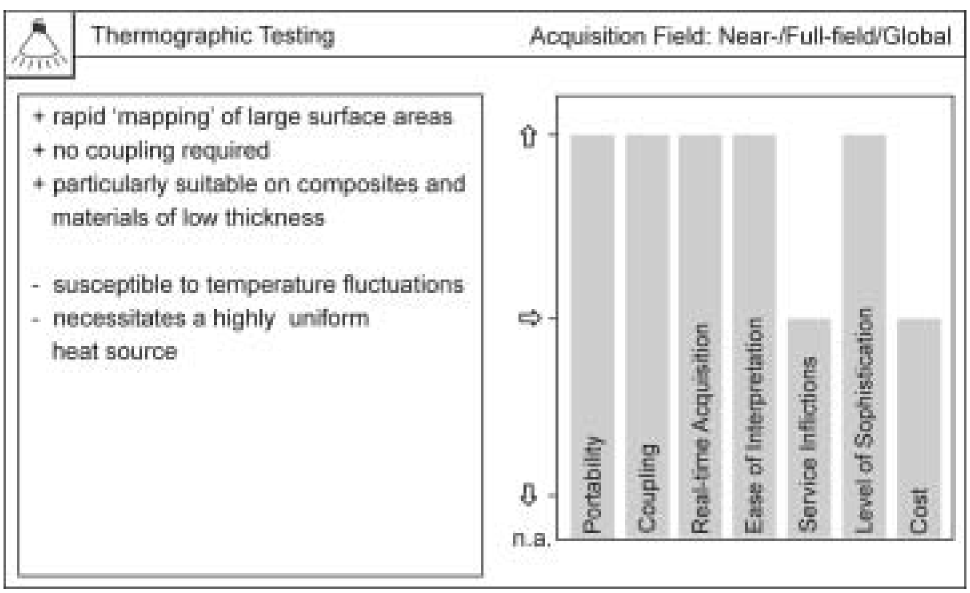
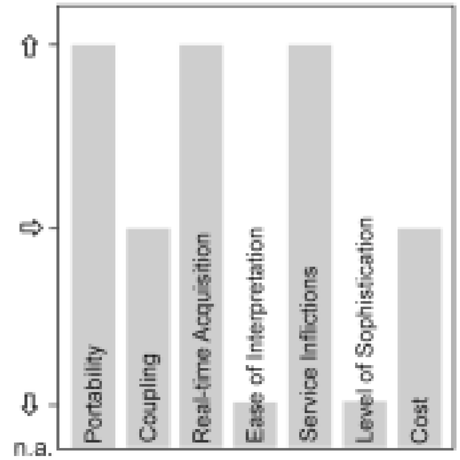


Table 4: Practicality Matrices (continued)

Eddy Current Testing — Acquisition Field: Near-field

+ no coupling agent required
+ mobile units

- mostly used in testing of metallic parts
- difficult to interpret
- only sensitive to conductive materials, hence matrix-related defects go undetected



Optical Methods (Shearography) — Acquisition Field: Near-/Full-field

+ high detail even if operated at full-field level
+ no coupling or immediate contact required
+ comprehensive full-field inspection method with excellent sizing capabilities

- structure must be exposed to controlled loading conditions
- relatively high environmental stability requirements
- less established

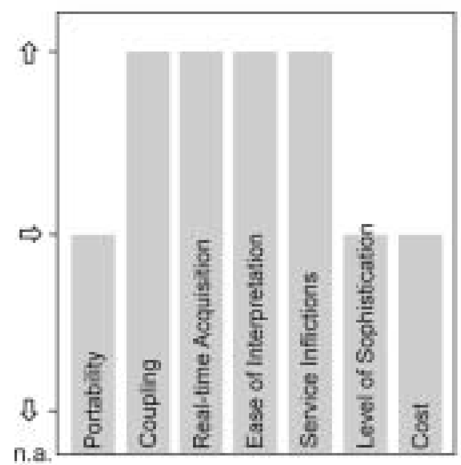
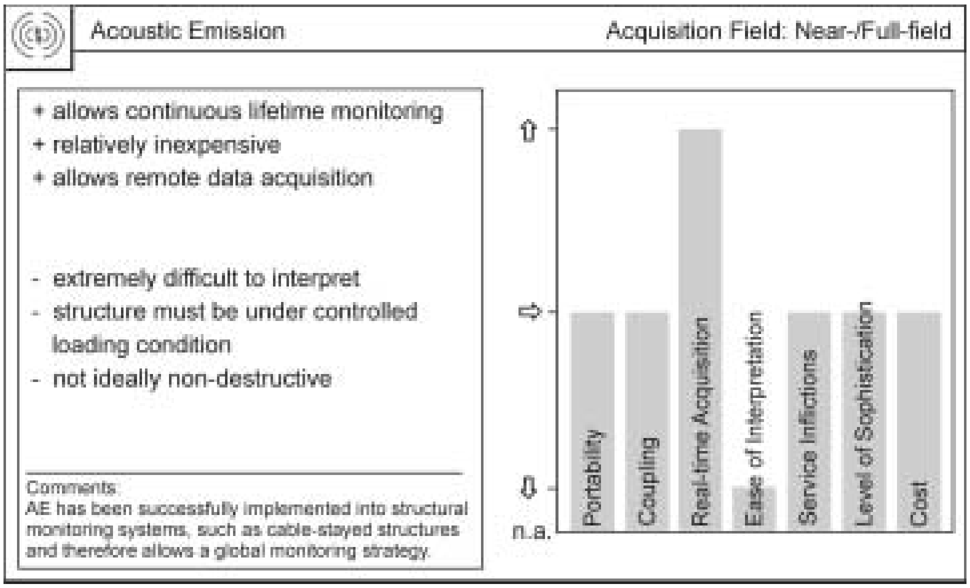


Table 4: Practicality Matrices (continued)



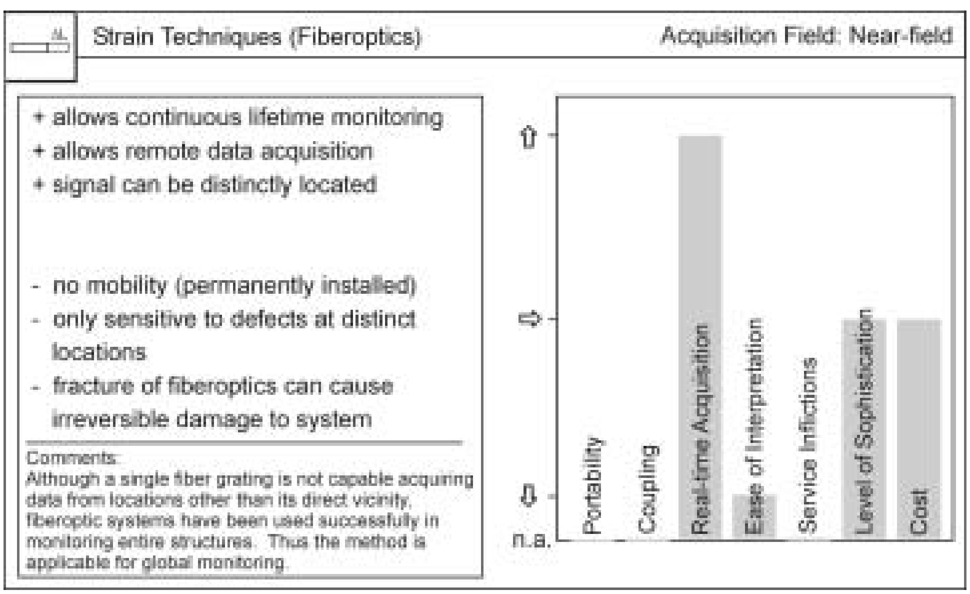
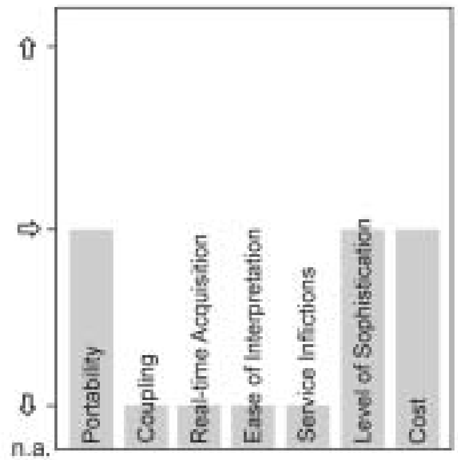


Table 4: Practicality Matrices (continued)

Modal Analysis — Acquisition Field: Global

+ allows assessment of entire structure
+ mobile and relatively inexpensive equipment

- substantial computational effort that restricts in-situ data interpretation
- rarely realizable without traffic inflictions
- representative and reproducible results can only be obtained under stable environmental conditions



Ground-Penetrating Radar — Acquisition Field: Full-field/Global

+ used extensively in the civil sector
+ high mobility
+ no coupling required

- little to no background information on applicability to composite materials
- generally unsuitable for inspection of thin materials
- relatively difficult to interpret

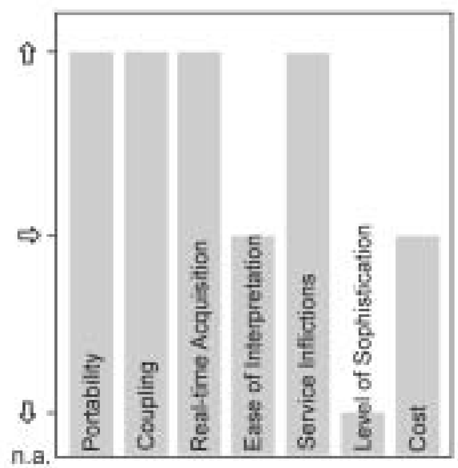
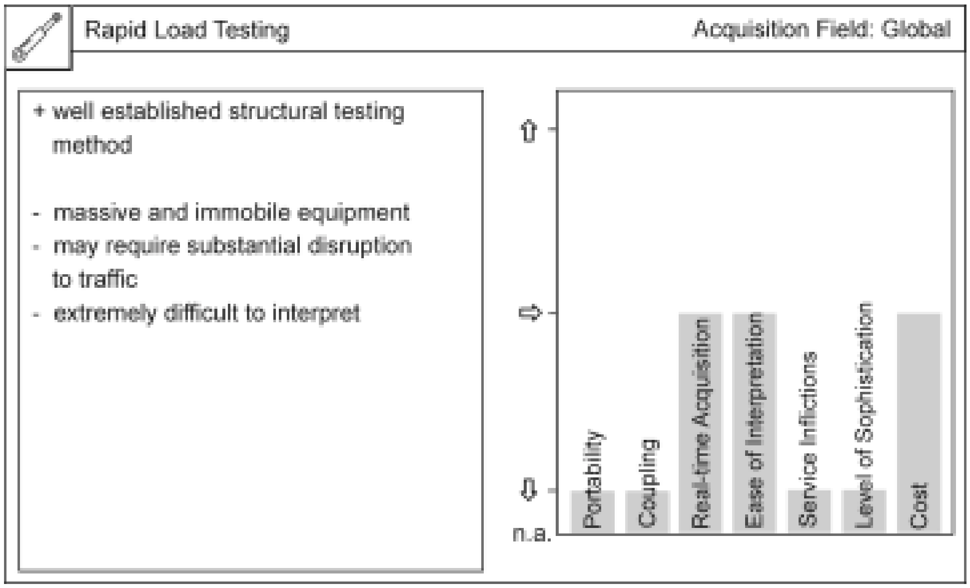


Table 4: Practicality Matrices (continued)



16.4 RANKING MATRIX

All previous considered, the final ranking matrix (RM) can now be assembled. As outlined, it entails all of the discussed methods, ranked according to a combination of detectability, practicality, and eventual stringent requirements, as outlined in Figure 16-1. Herein, selected methods will be classified as *primary* choices, as they show superior applicability over the remaining field. This superiority is mostly expressed in terms of defect detectability but can extend significantly into the practicality regime. As formerly mentioned, the primary category shall include techniques applicable in both full-field and near-field inspection. Again, the basic methodology proposed by the authors is to first inspect a structure for defects on a full-field scale with subsequent detailed analysis of any discontinuous regions.

Secondly, a subset of *conditional* choices will be given. Their applicability largely depends on the specific inspection objective and/or site conditions. As mentioned in a preceding report [1], a majority of defects found in CFRP are of relatively small dimension and thus give preference to near- and full-field inspection techniques. However, if a global assessment on structural integrity shall be established, near- and full-field methods are mostly inappropriate choices. Further, in well-controlled environments, practical drawbacks may be less pronounced and enable use of methods than require a more complex test setup.

Thirdly, a number of methods will be classified as *supplementary* to those of primary choice. Supplementary methods should be applicable in the near- to full-field range, portable and inexpensive, yet provide information on material properties that cannot be extracted from the two primary methods.

Lastly, the RM will address methods that were shown to have significantly lower applicability and should hence be *excluded* from the list of viable methodologies. Such inapplicability is implied by either the high uncertainty and/or profound insensitivity towards a large number of defects, significant restrictions in practicality, or certain stringent requirements that extend past the issues addressed by the DM and PM matrices.

Prior to presentation of the RM, the rationale will again be outlined in a systematic manner, as to provide the reader with conclusive information on why certain decisions were made.

16.4.1 Primary Methods

Primary methods shall combine a generally high defect-sensitivity with capabilities of locating and, ideally, sizing of each individual defect. As may be seen from Table 3, this precondition is satisfied, within limitations, by ultrasonics, thermography, shearography, as well as radiographic imaging. While latter is undoubtedly the most transparent of all method, its stringent safety requirements, implied by the utilization of aggressive x- or γ-radiation, may often restrict a flexible use in field environments. Hence, thermography, optical methods and ultrasonics remain as possible methods, where it should be pointed out that latter is largely restricted to localized inspection, while thermography and optical methods can be applied in both near- and full-field manner.

While the stringent requirement of external loading in optical testing appears to add to the complexity of the inspection procedure, it should be considered that service load levels might often be of sufficient magnitude to expose a majority of the internal deficient regions. In contrast, defects located in regions of negligible strain levels are likely to go undetected. Nevertheless, optical methods have shown to provide strain patterns of excellent geometric clarity.

Presently, sensitivity of both methods to a variety of defects remains largely unknown. This is in part conditioned by the fact that a majority of past research work has been focused on inspection of a very limited range of defects, most of which were either delamination, impact-related damage or voids of rather significant magnitude. Hence, both methods are given equal potential and must be subject to future investigation.

16.4.2 Conditional Methods

Considering the characteristics of radiographic testing and modal analysis discussed is previous sections, their drawbacks for safe, economical and, in latter case, detailed analysis of defects have become apparent. Nevertheless, if site conditions allow use of radiographic equipment, i.e. supply a source capable of providing the several kilovolts required for operation and further allow its safe use, the high transparency can most certainly be of considerable advantage.

Alternatively, as supported by numerous reports, the impact of material degradation on global structural response can most successfully be monitored using modal data [7]. As evaluation of global behavior remains one the primary objectives in structural testing, modal analysis must be considered a viable, though in view of the resent report, conditional method.

16.4.3 Supplementary Methods

Traditionally, visual- and acoustic impact testing have been the methods of choice to perform fast and preliminary inspections on composite materials. To date, similar methodology has been followed for rapid in-situ quality assessment of CFRP overlays. This was mostly dictated by the fact neither method demands extensive background knowledge on material properties, operation of equipment or signal interpretation. As such, visual inspection precedes virtually all automated test procedures. Hence, instead of treating VT as a separate NDE technique, it should much rather be considered a precondition for all further inspection, simply due to its simplicity and extreme flexibility.

Moreover, VT and AIT are both inexpensive and have proven to detect defects, which are often of primary interest, namely medium to large delamination, considerable moisture accumulation, and severe fiber misalignment. Hence, both methods are proposed to serve as additional tools in assessing the quality of CFRP overlays. Nevertheless, it should be emphasized that neither method possesses adequate detectability necessitated for a comprehensive quality assessment.

16.4.4 Excluded Methods

The majority of the remaining techniques have been excluded due to their typically low detectability (compare Table 3). These include penetrant- and eddy current techniques. Although fiberoptic sensors and acoustic emission systems have proven suitable lifetime monitoring systems for new and existing structures, data from such systems is often lacks sufficient interpretability. As such, localization and sizing of defects through mere detection of stress concentrations or acoustic activity at fracture a surface remains difficult. In existing structures, sensor cannot be situated at the concrete/composite interface or at interlaminar locations, which are the regions of high interest.

Table 5: Ranking matrix

RANKING	METHOD	COMMENTS
PRIMARY METHODS	*Thermography (TIR)* † *Shearography* † *Ultrasonics (UT)* ††	† Both methods are proposed for near- and full-field monitoring, however, one may yield higher applicability over the other, which must be confirmed through future experimental investigation. †† Ultrasonics must be considered applicable for near-field inspection, exclusively. It's extensive background and range of instrumentation makes it especially favorable
CONDITIONAL METHODS	*Radiographic Testing (RT)* *Modal Analysis*	*Applicability of these methods is largely dependent on site conditions and detail of inspection. For highly detailed inspection in controlled environments (i.e. access to adequate power supply, no concern of safety) RT remains a favorable technique. In contrary, for changes in structural response through material degradation, modal analysis provides most conclusive results.*
SUPPLEMENTARY METHODS	*Visual Testing (VT)* *Acoustic Impact Testing (AIT)*	*These methods are proposed as supplementary, mostly due to their general ease of use and extremely high flexibility. Moreover, they can be applied in simplistic form and do not necessitate extensive background knowledge in theory and/or application of the technique. The reader should be reminded, however, that neither method is of such transparency or level of sophistication that is could be considered solely for comprehensive in-situ inspection.*
EXCLUDED METHODS	*Penetrant Testing* [1] *Eddy Current Testing (ET)* [2] *Acoustic Emission (AE)* [3] *Strain Measurement Techniques (Fiberoptics)* [4] *Ground-Penetrating Radar (GPR)* [5] *Rapid Load Testing* [6]	*Quick-Reference List:* - *Low detectability* [1,2,4,5,6] - *Presumed inadequate for defect localization* [3,6,8] - *Presumed inadequate for defect sizing* [3,4,5,6]

17 CONCLUSIONS

As CFRP composites continue to gain acceptance in structural rehabilitation of deteriorating infrastructure, the consequent need for comprehensive and rapid in-situ quality assessment has arisen. Conditioned by the inevitable presence of material-, installation-, and service-induced defects, many rehabilitation schemes are likely to undergo deterioration to a level where they become ineffective, presupposing defects go undetected and are not restricted from further propagation at an early stage. At present, field methodologies encompass the rather simplistic inspection through visual inspection or surface tapping. Though applicable, these methods are largely inadequate in assessing the overall ‘health’ of rehabilitation schemes. Hence, alternative means for early detection and characterization of such defects must be developed.
From the preceding discussion it was shown that non-destructive testing methodologies, as currently applied to CFRP-rehabilitated components, are often insufficient in providing field inspectors and engineers with comprehensive information on bond-, material-, and geometrical deficiencies located within the concrete/composite hybrid. These include visual inspection and acoustic impact testing, latter commonly practiced in form of a ‘coin tap’ test. Given this insufficiency, authors have evaluated a multitude of alternative non-destructive inspection methods upon their potential for in-situ quality assessment of CFRP-rehabilitated structures. Apart from methodologies currently applied in the civil sector, a variety of so-called ‘traditional’ NDE techniques, as well as methods lately progressed to become accepted ‘state-of-the-art’ techniques, were discussed. More specifically, this investigation was aimed at identifying a limited number of primary NDE methods that appear most suitable for in-situ testing of CFRP-rehabilitated infrastructure.
It was shown that suitability of field techniques often demands rapid and comprehensive detection of defects, without imposing negligible importance on factors like mobility, flexibility or ease of interpretation. Finally, primary NDE methods should be complementary to each other, i.e. inspection should be initiated on a full-field level with subsequent detailed inspection utilizing the more sensitive near-field technique.

In the present report, fundamental theory, common means of instrumentation, recent application to CFRP composites, as well as capabilities and limitations of each individual NDE technique have been addressed. Subsequently, methods were classified according to a predefined ranking scheme. Herein, detectability was given paramount importance. However, some methods appeared to impose such stringent requirements on site-, loading-, or environmental conditions that they were excluded solely on these premises. Ultimately, three methods were identified to be particularly suitable given their most favorable combination of detectability and practicality, including

- Ultrasonics,
- Thermography, and
- Shearography

In addition, authors proposed two further methods as viable supplementary techniques, mainly due to a combination of low cost and simplicity, namely

- Visual testing, and
- Acoustic impact testing

Despite the widespread use of non-destructive testing methodologies in the field of laminated composite materials, most experimental work has been aimed solely at inspecting ‘traditional’ laminates, including thin plates or sandwich structures, as they are commonly utilized in the aerospace sector. However, limited work has been presented in the field of concrete-composite hybrid components. The reader should thus be reminded that findings presented in this report are based predominantly on results of experimental work performed on these ‘traditional’ composites. Eventually, detectability and practicality of each method as they apply to in-situ inspection of CFRP-rehabilitated infrastructure must be evaluated and confirmed through further investigation.

18 ANNOTATION

Λ	=	Spatial period of optical fiber grating
A	=	Area normal to heat flow [m^2]
A'	=	Absorbed energy component
c	=	Speed of light = 2.9979×10^8 [m/s]
C_c	=	Speed of compression wave [m/s]
C_s	=	Speed of shear wave [m/s]
D	=	Diameter of transducer [mm]
E	=	Young’s modulus of elasticity [N/mm^2]
f	=	Frequency [Hz]
G	=	Shear modulus [N/mm^2]
$i°$	=	Angle of incidence
k	=	Thermal conductivity [W/m^2-°C]
N	=	Moiré fringe order
n_{eff}	=	Refractive index of optical fiber core
p	=	Pitch of grating [mm]
Q	=	Heat energy [W]
R	=	Coefficient of reflection [%]
$r°$	=	Angle of refraction
R'	=	Reflected energy component
T	=	Absolute temperature [°C]
t	=	Material thickness [m]
T'	=	Transmitted energy component
u	=	Component of deflection [mm]
V_1	=	Velocity in medium 1 [m/s]
V_2	=	Velocity in medium 2 [m/s]
V_c	=	Compression wave velocity [m/s]
V_f	=	Fiber volume fraction [%]
V_s	=	Shear wave velocity [m/s]
Z	=	Acoustic impedance [kg/m^2s]

Z_1	=	Acoustic impedance in material 1 [kg/m^{2}s]
Z_2	=	Acoustic impedance in material 2 [kg/m^{2}s]
Z_e	=	Electromagnetic impedance
ΔT	=	Temperature difference [°C]
$\Delta\lambda_B$	=	Change in reflective wavelength
K_ε	=	Theoretical gauge constant, determined experimentally [86]
δ	=	Standard depth of penetration [mm]
ε	=	Emissivity
ε_0	=	Dielectric permittivity of free space = $8.854*10^{-12}$ [Fm^{-1}]
ε_r	=	Relative dielectric constant
ε_x	=	Strain component in x-direction
ε_y	=	Strain component in y-direction
ϕ	=	Half the angle between propagation axes of two laser beams
γ_{xy}	=	Shear strain component
λ	=	Wavelength [m]
λ_1	=	Wavelength of light [m]
λ_B	=	Reflective wavelength of optical fiber [m]
μ_0	=	Magnetic permeability of free space
μ_r	=	Relative permeability
$\mu\varepsilon$	=	Microstrain [10^{-6}]
ν	=	Poisson’s ratio
θ	=	Angle of beam spread [deg]
ρ	=	Material density [kg/m^3]
ρ_e	=	Electrical resistivity [μΩ-cm]
σ	=	Stefan-Boltzmann constant = $1.38*10^{-23}$ [JK^{-1}]
ξ_0	=	Coefficient of thermo-optic component and thermal expansion = $6*10^{-6}$ [°C^{-1}] (nominal)

19 APPENDIX

In the following, some of the most essential formulations in NDE are provided. They serve towards a more thorough understanding of some of the previously discussed methods. In Section 19.5, numerous important material parameters for NDE inspection are given. It must be understood that these values have been obtained from specific references. In most cases, minute changes in material composition will likely alter these values by a significant degree. These include changes in fiber volume fraction in CFRP composites, temperature fluctuation, as well as moisture absorption or variation in concrete aggregate size.

While a comprehensive theoretical discussion of most techniques would go beyond the scope of this report, the authors refer to literature, in which a complete background theory for most methods can be obtained, including [6], [39], [34], [53] and [83].

19.1 ULTRASONICS

As discussed in Section 5.1.1, different waveforms can be generated and transferred through a material. The most common form of waves are P- and S- waves. The velocity for a compressive wave for a material is given as

$$V_c = \sqrt{\frac{E}{\rho} \cdot \frac{1-\upsilon}{(1+\upsilon)\cdot(1-2\cdot\upsilon)}} \qquad (10)$$

The shear wave velocity can be calculated from

$$V_s = \sqrt{\frac{E}{\rho} \cdot \frac{1}{2\cdot(1+\upsilon)}} \qquad (11)$$

or alternatively

$$V_s = \sqrt{\frac{G}{\rho}} \qquad (12)$$

In close vicinity (near field), the diameter of the beam and transducer crystal can be assumed to be of equal size [6]. Beyond a certain distance, the beam is likely to spread out like a cone, where beam spread is governed by the following equation

$$\sin\frac{\theta}{2} = \frac{1.22\lambda}{D} \qquad (13)$$

19.2 EDDY CURRENT TESTING

An exponential decay of eddy current is experienced below the surface of the material that is penetrated. The standard depth of penetration is defined as the depth at which the eddy current strength has reduced by 37% relative to the initial surface strength [50]. Depending on frequency of the induction coil, this value is given as

$$\delta = 25 \cdot \sqrt{\frac{\rho_e}{f \cdot \mu_r}} \qquad (14)$$

where δ is in units of [mm].

19.3 OPTICAL METHODS

In conventional geometrical moiré, the relative displacement between specimen and master grating can be found from

$$u = N \cdot p \qquad (15)$$

From the stress-strain relationship of materials one obtains the three strain components

$$\varepsilon_x = p \frac{\partial N_x}{\partial x} \qquad (16)$$

$$\varepsilon_y = p \frac{\partial N_y}{\partial y} \qquad (17)$$

$$\gamma_{xy} = p \left(\frac{\partial N_x}{\partial x} + \frac{\partial N_y}{\partial y} \right) \qquad (18)$$

In moiré interferometry, the intersection of two laser beams at an angle 2ϕ produces a reference grating. The distance between adjacent fringes, i.e. fringe spacing of the grating is given by

$$D = \frac{\lambda_l}{2} \cdot sin\,\phi \qquad (19)$$

19.4 STRAIN MEASUREMENT TECHNIQUES

Strain variation in optical fiber measurements is derived from shift in the wavelength arriving at the optical sensor. According to Bragg’s law, the reflective wavelength can be expressed as

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda \qquad (20)$$

By considering effects arising from thermal expansion and mechanical strain, the expansion of the optical fiber can be calculated from

$$\Delta\lambda_B = K_\varepsilon \cdot \varepsilon_1 + \lambda_B \cdot \xi_0 \cdot \Delta T \qquad (21)$$

19.5 Material Constants for NDE Testing

Table 6: Material Constants in NDE

Material Property		Air	Water	Steel	CFRP*	Concrete
Density, ρ	[kg/m^3]	1.275	1,000	7,800	1,620	1,900-2,300
P-Wave Speed, C_c	[m/s]	330	1,483	5,900	- (3)	3,600- 4,500
S-Wave Speed, C_s	[m/s]	- (2)	- (2)	3,230	- (3)	- (3)
Thermal Conductivity, k	[W/m-°C]	0.026	0.65	54	54.4 / 0.72	1.37
Electrical Resistivity, ρ_e	[μΩ–cm]	∞	10^5-10^8	45	$3.3\cdot10^3$-10^4 / $1.5\cdot10^5$-$5\cdot10^7$	10^5-10^7
Relative Permeability, μ_r	[ ]	1.0	1.0	100	- (3)	- (3)
Emissivity, ε	[ ]	- (2)	0.99	0.35/0.16 (1)	0.8-1.0	0.92

* Values for CFRP are dependent on fiber direction. Top values give properties parallel to fibers and bottom values give that in transverse direction
(1) Alloy/Polished (2) Not applicable (3) Not made available

20 GLOSSARY

A-scan	Ultrasonic data representation using instantaneous data that is displayed on a horizontal baseline (distance or time of flight) versus a vertical deflection (amplitude).
Adherent	A body that is held to another body usually by an adhesive.
Adhesive	Substance capable of holding two materials together by surface attachment. Can be a film, paste of liquid.
Attenuation	Factor representing a decrease in signal intensity with distance. Expressed in decibels (dB) per unit distance.
Black light	Electromagnetic radiation in the range of 315-400 nm.
Bond strength	The amount of adhesion between two surfaces.
Boroscope	Industrial scope that transmits images from inaccessible regions for visual inspection. They can be flexible or rigid in nature.
B-scan	Ultrasonic data representations along a line scan that represent one particular cross-section of a part. Interior features can be displayed in their approximate length.
BVID	Barely visible impact damage.
Capillary action	Movement of liquids within the spaces of a porous material due to forces of adhesion, cohesion, and surface tension.
Catalyst	A substance that changes the rate of chemical reaction without itself undergoing permanent change in composition.
CCD	Charge coupled device, used to obtain electronic signals in modern video cameras.
Coherence	Multiple events (i.e. emission of light rays) that occur at an identical time instant (temporal coherence) while originating from the same location in space (spatial coherence).
Cold bond	Separation within a material or at the interface between two adjacent materials which are in intimate contact but possess no capability of stress transfer.
Collimated light	Plane wave front comprised of coherent light.
Compression wave	A wave in which the direction of particle motion coincides with direction of wave propagation.
Conduction	Heat transfer through interaction of atoms and molecules, mostly encountered in solids.

Convection	Heat transfer in fluids by mixing of molecules.
Cryogenics	Chemicals used to obtain extremely low temperatures at around -180°C (i.e. liquid nitrogen).
CSC	Curved-surface-correction feature applied in ultrasonic test units for sound path correction when inspecting around the circumference of a curved surface.
C-scan	Ultrasonic data representation that provides a plan view of material constitution, including internal discontinuities.
DAC	Distance amplitude correction in ultrasonic units that automatically adjusts amplitude in regions of varying signal intensity.
Debond	An initially unbonded or nonadhered region between two adherents. Also used to describe a separation at the fiber-matrix interface. In the construction industry, debond and delamination are sometimes used interchangeably when referring to separations at the concrete-composite interface.
Decibel (dB)	Logarithmic scale expressing relative amplitude or intensity of ultrasonic signals.
Degradation	Deleterious change in physical properties or appearance.
Delamination	Separation of the layers of material in a laminate, either local or covering a wide area.
Delay line	Column of material such as Plexiglas that behaves similar to a water path and allows a shift of the initial ultrasonic pulse.
Disbond	An area within an initially bonded interface between two adherents in which adhesion failure or separation has occurred.
DMTA	Dynamic mechanical thermal analysis. Provides information on presence of solvents, changes in structure and chemical reactions.
DSC	Differential scanning calorimetry. Detects loss of solvents and other volatiles.
Dye penetrant	Visible or fluorescent solution that seeps into porous surfaces.
Electrical conductivity	Readability of a material to allow flow of electric current.
Emissivity	Ability to radiate energy relative to a perfect radiator (blackbody) with values ranging from zero to one.

Emulsifier	Liquid that interacts with an oily substance to make it water-soluble.
Ferromagnetic	Materials that are strongly attracted to a magnet and can become magnetized, such as iron.
Fiberscope	Device that delivers light through a fiberoptic bundle to a CCD unit that converts it into an electric signal.
Galvanic corrosion	Galvanic reaction between metals and conductive carbon fibers, resulting in degradation of matrix and metal.
Half-life	Measure of the average lifetime of a radioactive substance, where one half-life represents the time required for one half of any given quantity of the substance to decay.
Heat mirror	A perfect light reflector with extremely low emissivity.
Hydrolysis	Process of degradation that generically includes the splitting of chemical bonds and the addition of water.
Hybrid	The combination of two materials of different origin or composition.
Inclusion	Mechanical discontinuity occurring within a material, consisting of a solid, encapsulated material.
Interface	Boundary between two different, physically distinguishable media.
Kissing bond	See *cold bond*
Lamb wave	Surface waves that travel between two parallel surfaces by means of elliptical particle motion, such as inside a plate.
Laminate	A product made by stacking of multiple layers of unidirectional fibers or oriented fiber configurations embedded in a resin matrix.
Longitudinal wave	See *compression wave*
LVDT	Linear variable differential transformer
Mode conversion	Phenomenon where wave modes are altered due to refraction at material boundaries.
NDE	Non-destructive evaluation. Methodology encompassing the use of non-destructive testing (NDT) techniques with subsequent assessment on severity in view of performance or integrity of an entire structure or components thereof.
NDI	Non-destructive inspection, often synonymous to *NDT*.
NDT	Non-destructive testing. A process that does not result in any damage or change to the material or part under

	examination and through which the presence of conditions or discontinuities can be detected.
Photons	Particles composing light and other forms of electromagnetic radiation, possessing no mass or charge.
Piezoelectric crystal	Material that transforms electrical energy into mechanical energy and vice versa.
Pitch	Distance between adjacent lines of a grating.
Plate wave	See *lamb wave*
Porosity	Trapped pockets of air, gas or vacuum within a solid material, typically less than 10μm in diameter.
Pot life	Time a thermosetting resin retains a viscosity low enough to be used in processing.
Prefabricated material	Composite material manufactured and cured under controlled factory conditions with a generally high material uniformity and used in cured state in the field.
Prepreg	Ready-to-mold material in sheet form impregnated with resin and stored for use. The resin is partially cured at a B-stage.
Probe	See *transducer*
P-wave	See *compression wave*
Quasi-isotropic	Laminate, whose extensional stiffness properties behave like those of an isotropic material.
Radiation	Transfer of heat energy in form of electromagnetic waves.
Rayleigh wave	Surface waves that travel predominantly in media with only a single surface.
Reproducibility	Ability to obtain identical test results under repeated testing.
Rheology	The study of flow of materials, particularly plastic flow of solids.
Saponification	Specific form of hydrolysis involving alkalis.
Sensitivity	Measure of the smallest feature inside a material that produces a discernible signal.
Shear wave	A wave in which the direction of particle motion is perpendicular to the direction of wave propagation.
Shelf life	Length of time a material can be stored under specific environmental conditions and continue to meet all applicable specification requirements.

Stoichiometry	quantitative relationship between constitutions in a chemical system.
S-wave	See *shear wave*
Thermal conductivity	Rate at which heat flows through a body.
Transducer	Device used to produce mechanical stress waves.
Transverse wave	See *shear wave*
T_g	Temperature at which increased molecular mobility results in significant changes in the properties of a cured resin system.
TVG	Time-varied-gain feature in ultrasonic test units that corrects for distance/amplitude variations due to attenuation or beam spreading.
Undercure	A condition resulting from the allowance of too little time and/or temperature for adequate hardening.
Vitrification	Process of conversion into a glassy phase.
Voids	air or gas that has been cured into a laminate or an interface between two adherents. Porosity is an aggregation of microvoids.
Volatiles	Materials, such as water or alcohol, in a resin formulation that are capable of being driven off a vapor at room temperature or at a slightly elevated temperature.
Wetability	The ability of a liquid to adhere to a surface.

21 REFERENCES

1. Kaiser, H. and V.M. Karbhari, *Quality and Monitoring of Structural Rehabilitation Measures - Part 1: Description of Potential Defects*. 2001, University of California, San Diego: La Jolla, CA. p. 60.
2. Birt, E.A., *Damage Detection in Carbon-Fibre Composites Using Ultrasonic Lamb Waves.* Insight, 1998. **40**(5): p. 335-339.
3. Wong, B.S., et al., *Thermographic Evaluation of Defects in Composite Materials.* Insight, 1999. **41**(8): p. 504-509.
4. Grimberg, R., et al., *Eddy Current Holography Evaluation of Delamination in Carbon-Epoxy Composites.* Insight, 2001. **43**(4): p. 260-264.
5. Zhang, Y., et al., *Damage Growth Investigation in a Random Fiber Composite Beam by Moire Interferometry.* Journal of Composite Materials, 1998. **32**(7): p. 664-678.
6. Hellier, C.J., *Handbook of Nondestructive Evaluation*. 2001, New York: McGraw-Hill.
7. Stubbs, N., et al., *A global non-destructive Damage Assessment Methodology for Civil Engineering Structures.* International Journal of Systems Science, 2000. **31**(11): p. 1361-1373.
8. Green, J.R.E., *Advanced NDE Techniques for Manufacturing and Construction Application*, in *Nondestructive Testing and Evaluation for Manufacturing and Construction*, H.L.M. dos Reis, Editor. 1990, Hemisphere Publishing Corporation: New York. p. 1-16.
9. Bartlett, S.W. and J. Duke, J. C., *Nondestructive Evaluation of Complex Geometry Advanced Material Components*, in *Nondestructive Testing and Evaluation for Manufacturing and Construction*, H.L.M. dos Reis, Editor. 1990, Hemisphere Publishing Corporation: New York. p. 17-25.
10. Connolly, M.P., *The Measurement of Porosity in Composite Materials Using Infrared Thermography.* Journal of Reinforced Plastics and Composites, 1992. **11**(12): p. 1367-1375.
11. Hawkins, G.F., E. Johnson, and J. Nokes, *Typical Manufacturing Flaws in FRP Retrofit Applications.* Concrete Repair Bulletin, 1998: p. 14-17.
12. Hertwig, M., T. Flemming, and R. Usinger, *Speckle Interferometry for Detection of Subsurface Damage in Fibre-reinforced Composites.* Measurement Science and Technology, 1994. **5**: p. 100-104.
13. Gregory, R., *Laser Shearography Inspection for Aircraft and Space Structures.* Insight, 2001. **43**(3): p. 150-154.
14. Kundu, T., et al., *C-Scan and L-Scan Generated Images of the Concrete/GFRP Composite Interface.* NDT & E International, 1999. **32**: p. 61-69.
15. Mei, Z.M. and D.D.L. Chung, *Effects of Temperature and Stress on the Interface Between Concrete and Its Carbon Fiber Epoxy-Matrix Composite Retrofit, Studied by Electrical Resistance Measurement.* Cement and Concrete Research, 2000. **30**: p. 799-802.
16. Cawley, P. and R.D. Adams, *The Mechanics of the Coin-tap Method of Non-destructive Testing.* Journal of Sound and Vibration, 1988. **122**: p. 299-316.

17. Mackie, R.I. and A.E. Vardy, *Applying the Coin-Tap Test to Adhesives in Civil Engineering: A Numerical Study.* International Journal of Adhesion and Adhesives, 1990. **10**(3): p. 215-220.
18. Haque, A. and R.P. K, *Sensitivity of the Acoustic Impact Technique in Characterizing Defects/Damage in Laminated Composites.* Journal of Reinforced Plastics and Composites, 1995. **14**: p. 280-296.
19. Wu, H. and M. Siegel, *Correlation of Accelerometer and Microphone Data in the "Coin Tap Test".* IEEE Transactions on Instrumentation and Measurement, 2000. **49**(3): p. 493-497.
20. Raju, P.K., J.R. Patel, and U.K. Vaidya, *Characterization of Defects in Graphite Fiber Based Composite Structures Using the Acoustic Impact Technique (AIT).* Journal of Testing and Evaluation, 1993. **21**(5): p. 377-395.
21. McMaster, R.C., ed. *Nondestructive Testing Handbook*. Vol. 2: Liquid Penetrant Tests. 1982, American Society for Metals: Metals Park, OH.
22. Krautkrämer, J. and H. Krautkrämer, *Ultrasonic Testing of Materials*. 4 ed. 1990, Berlin: Springer-Verlag. 675.
23. Tan, K.S., et al., *Comparison of Lamb Waves and Pulse Echo in Detection of Near-Surface Defects in Laminate Plates.* NDT & E International, 1995. **28**(4): p. 215-223.
24. Lanza di Scalea, F., M. Bonomo, and D. Tuzzeo, *Ultrasonic Guided Wave Inspection of Bonded Lap Joints: Noncontact Method and Photoelastic Visualization.* Research in Nondestructive Evaluation, 2001. **13**: p. 1-19.
25. Castaings, M. and B. Hosten, *Lamb and SH Waves Generated and Detected by Air-Coupled Ultrasonic Transducers in Composite Material Plates.* NDT & E International, 2001. **34**: p. 249-258.
26. Buckley, J., *Principles and Applications of Air-coupled Ultrasonics.* Insight, 1998. **40**(11): p. 755-759.
27. Scarponi, C. and G. Briotti, *Ultrasonic Technique for the Evaluation of Delaminations on CFRP, GFRP, KFRP Composite Materials.* Composites: Part B 31, 2000: p. 237-243.
28. Maslov, K. and T. Kundu, *Selection of Lamb Modes for Detecting Internal Defects in Composite Laminates.* Ultrasonics, 1997. **35**: p. 141-150.
29. Dewhurst, R.J. and B.A. Williams. *A Study of Lamb Wave Interaction with Defects in Sheet Materials Using a Differential Fibre-Optic Beam Deflection Technique*. in *Seventh International Symposium on Nondestuctive Characterization of Materials*. 1995. Prague, Czech Republic: Transtec Publishing.
30. Lowe, M.J.S. and P. Cawley, *The Applicability of Plate Wave Techniques for the Inspection of Adhesive and Diffusion Bonded Joints.* Journal of Nondestructive Evaluation, 1994. **13**: p. 185-200.
31. Seale, M., B.T. Smith, and W.H. Prosser, *Lamb Wave Assessment of Fatigue and Thermal Damage in Composites.* Journal of the Acoustical Society of America, 1998. **103**(5, Pt. 1): p. 2416-2424.
32. Jones, T.S. and G. Lubin, *Nondestuructive Evaluation Methods for Composites*, in *Handbook of Composites*, S.T. Peters, Editor. 1998, Chapman & Hall: London. p. 838-856.

33. Kim, N. and J.D. Achenbach, *Quantitative Characterization of Multiple Delaminations in Laminated Composites Using the Compton Backscatter Technique.* Journal of Nondestructive Evaluation, 1998. **17**(2): p. 53-65.
34. Bray, D.E. and R.K. Stanley, *Nondestructive Evaluation : A Tool in Design, Manufacturing, and Service*. 1997, Boca Raton: CRC Press. 586.
35. Poranski, C.F., E.C. Greenawald, and Y.S. Ham. *X-Ray Backscatter Tomography: NDT Potential and Limitations*. in *Seventh International Symposium on Nondestuctive Characterization of Materials*. 1995. Prague, Czech Republic: Transtec Publishing.
36. Demeis, R., *CAT Scanning Composites.* Aerospace America, 1991. **29**(2): p. 44-45.
37. Bossi, R.H. and G.E. Georgeson, *Composite Structure Development Decisions Using X-ray CT Measurements.* Materials Evaluation, 1995. **53**(10): p. 1198-1203.
38. Henneke II, E.G., *Vibrothermography Applied to Polymer Matrix Composites*, in *Manual on Experimental Methods for Mechanical Testing of Composites*, C.H. Jenkins, Editor. 1998, The Fairmont Press: Lilburn, USA. p. 213-221.
39. Maldague, X.P.V., *Theory and Practice of Infrared Technology for Nondestructive Testing*. Wiley Series in Microwave and Optical Engineering, ed. K. Chang. 2001, New York: John Wiley & Sons, Inc. 684.
40. Jones, T. and H. Berger, *Thermographic Detection of Impact Damage in Graphite-Epoxy Composites.* Materials Evaluation, 1992. **50**(12): p. 1446-1453.
41. Brady, R.P., et al., *Thermal Image Analysis for the In-Situ NDE of Composites.* Journal of Composites Technology and Research, 1999. **21**(3): p. 141-146.
42. Titman, D.J., *Application of Thermography in Non-Destructive Testing of Structures.* NDT&E International, 2001. **34**: p. 149-154.
43. Maldague, X. and S. Marinetti, *Pulse Phase Infrared Thermography*. Journal of Applied Physics, 1996. **79**(5): p. 2694-2698.
44. Bai, W. and B.S. Wong, *Evaluation of Defects in Composite Plates under Convective Environments Using Lock-in Thermography*. Measurement Science and Technology, 2001. **12**: p. 142-150.
45. Lin, S.S., *Frequency Dependent Heat Generation During Vibrothermographic Testing of Composite Materials*. 1987, Virginia Polytechnic Inst. and State Univ.: Blacksburg, VA.
46. Rantala, J., D. Wu, and G. Busse. *Lock-In Vibrothermography Applied for Nondestructive Evaluation of Polymer Materials*. in *Seventh International Symposium on Nondestuctive Characterization of Materials*. 1995. Prague, Czech Republic: Transtec Publishing.
47. Lane, S.S., et al., *Eddy Current Inspection of Graphite/Epoxy Laminates.* Journal of Reinforced Plastics and Composites, 1991. **10**(2): p. 158-166.
48. Degtyar, A.D. and L.H. Pearson. *Ultrasonic and Eddy Current Characterization of Impact Damage in Graphite/Epoxy Rocket Motor Cases*. in *Review of Progress in Quantitative Nondestructive Evaluation*. 2000. Montreal, Canada: AIP.
49. Valleau, A.R., *Eddy Current Nondestructive Testing of Graphite Composite Materials.* Materials Evaluation, 1990. **48**(2): p. 230-239.

50. Gros, X.E., O. K, and K. Takahashi, *Eddy Current, Ultrasonic C-Scan and Scanning Acoustic Microscopy Testing of Delaminated Quasi-Isotropic CFRP Materials*. Journal of Reinforced Plastics and Composites, 1998. **17**(5): p. 389-405.
51. Ida, N., *Microwave NDT*. Developments in Electromagnetic Theory and Applications, ed. G.F. Roach. Vol. 10. 1992, Dordrecht, The Netherlands: Kluwer Academic Publishers.
52. Zoughi, R., S. Ganchev, and G.W. Carriveau. *Overview of Microwave NDE Applied to Thick Composites*. in *Seventh International Symposium on Nondestuctive Characterization of Materials*. 1995. Prague, Czech Republic: Transtec Publications.
53. Cloud, G., *Optical Methods of Engineering Analysis*. 1998, Cambridge: Cambridge University Press. 503.
54. Parks, V.J., *Geometric Moire*, in *Manual on Experimental Methods for Mechanical Testing of Composites*, C.H. Jenkins, Editor. 1998, The Fairmont Press, Inc.: Lilburn, USA. p. 137-146.
55. Hung, Y.Y., et al., *Evaluating the Soundness of Bonding using Shearography*. Composite Structures, 2000. **50**: p. 353-362.
56. Hung, Y.Y., *Computerized Shearography and It's Application for Nondestructive Evaluation of Composites*, in *Manual on Experimental Methods for Mechanical Testing of Composites*, C.H. Jenkins, Editor. 1998, The Fairmont Press: Lilburn, USA. p. 161-174.
57. Zanetta, P., et al., *Holographic Detection of Defects in Composites*. Optics & Laser Technology, 1993. **25**(2): p. 97-102.
58. Post, D., B. Han, and P. Ifju, *High Sensitivity Moiré : Experimental Analysis for Mechanics and Materials*. 1994, New York: Springer Verlag. 444.
59. Gryzagoridis, J., *Holographic Nondestructive Testing*, in *Nondestructive Testing and Evaluation for Manufacturing and Construction*, H.L.M. dos Reis, Editor. 1990, Hemisphere Publishing Corporation: New York. p. 451-462.
60. Steinchen, W., et al., *Non-destructive Testing of Aerospace Composite Materials using Digital Shearography*. Proceedings of the Institution of Mechanical Engineers Part G - Journal of Aerospace Engineering, 1998. **212**(NG1): p. 21-30.
61. Mizutani, Y., et al., *Fracture Mechanism Characterization in Cross-Ply Carbon-Fiber Composites Using Acoustic Emission Analysis*. NDT & E International, 2000. **33**: p. 101-110.
62. Mirmiran, A., M. Shahawy, and H. El Echary, *Acoustic Emission Monitoring of Hybrid FRP-concrete Columns*. Journal of Engineering Mechanics, 1999. **125**(8): p. 899-905.
63. Rizzo, P. and F. Lanza di Scalea, *Acoustic Emission Monitoring of Carbon-fiber-reinforced-polymer Bridge Stay Cables in Large-scale Testing*. Experimental Mechanics, 2001. **41**(3): p. 282-290.
64. Bohse, J., *Acoustic Emission Characteristics of Micro-failure Processes in Polymer Lends and Composites*. Composites Science and Technology, 2000. **60**: p. 1213-1226.
65. De Groot, P.J., P.A.M. Wijnen, and R.B.F. Jansen, *Real-time Frequency Determination of Acoustic Emission for Different Fracture Mechanisms in*

Carbon/Epoxy Composites. Composites Science and Technology, 1995. **55**: p. 405-412.

66. Lorenzo, L. and H.T. Hahn, *Static and Fatigue Fracture Monitoring in Unidirectional Composites by Acoustic Emission*, in *Nondestructive Testing and Evaluation for Manufacturing and Construction*, H.L.M. dos Reis, Editor. 1990, Hemisphere Publishing Corporation: New York. p. 67-85.
67. Ohtsu, M., T. Okamoto, and S. Yuyama, *Moment Tensor Analysis of Acoustic Emission for Cracking Mechanisms in Concrete.* ACI Structural Journal, 1998. **95**(2): p. 87-95.
68. Ohtsu, M., M. Shigeishi, and Y. Sakata, *Nondestructive Evaluation of Defects in Concrete by Quantitative Acoustic Emission and Ultrasonics.* Ultrasonics, 1998. **35**: p. 187-195.
69. Lim, M.K., *Impulse Radar Applications.* Concrete International, 2001. **23**(8): p. 64-68.
70. Bungey, J.H. and S.G. Millard, *Radar Inspection of Structures.* Proceedings of the Institution of Civil Engineers - Structures and Buildings, 1993. **99**(2): p. 173-186.
71. Bindi, L., G. Lenzi, and A. Saisi, *NDE of Masonry Structures: Use of Radar Tests for the Characterization of Stone Masonries.* NDT & E International, 1998. **31**(6): p. 411-419.
72. Colla, C., et al., *Comparison of Laboratory and Simulated Data for Radar Image Interpretation.* NDT & E International, 1998. **31**(6): p. 439-444.
73. Shaw, P. and J. Bergström, *In-Situ Testing of Reinforced Concrete Structures using Stress Waves and High-Frequency Ground Penetrating Radar.* Insight, 2000. **42**(7): p. 454-457.
74. Lau, K., et al., *Strain Monitoring in Composite-Strengthened Concrete Structures Using Optical Fibre Sensors.* Composites: Part B, 2001. **32**: p. 33-45.
75. Chan, P.K.C., et al., *Multi-Point Strain Measurement of Composite-Bonded Concrete Materials with a RF-Band FMCW Multiplexed FBG Sensor Array.* Sensors and Actuators, 2000. **87**: p. 19-25.
76. Uskokovic, P.S., et al., *Delamination Detection in Woven Composite Laminates with Embedded Optical Fibers.* Advanced Engineering Materials, 2001. **3**(7): p. 492-496.
77. Unknown, *Installation, Use and Repair of Fiber Optic Sensors*. 2001, University of Toronto: Ontario.
78. Bolton, R., et al., *Documentation of Changes in Modal Properties of a Concrete Box-girder Bridge due to Environmental and Internal Conditions.* Computer-Aided Civil and Infrastructure Engineering, 2001. **16**: p. 42-57.
79. Sanders, D.R., Y.I. Kim, and N. Stubbs, *Nondestructive Evaluation of Damage in Composite Structures Using Modal Parameters.* Experimental Mechanics, 1992. **32**(3): p. 240-251.
80. Ndambi, J.M., et al., *Comparison of Techniques for Modal Analysis of Concrete Structures.* Engineering Structures, 2000. **22**: p. 1159-1166.
81. Salawu, O.C. and C. Williams, *Review of Full-Scale Dynamic Testing of Bridge Structures.* Engineering Structures, 1995. **17**(2): p. 113-121.

82. Peeters, B., J. Maeck, and G. De Roeck, *Vibration-based Damage Detection in Civil Engineering: Excitation Sources and Temperature Effects.* Smart Materials and Structures, 2001. **10**: p. 518-527.

83. Ewins, D.J., *Modal Testing: Theory and Practice*. Mechanical Engineering Research Studies, ed. J.B. Roberts. 1984, Taunton, Somerset, England: Research Studies Press, Ltd. 269.

84. Hermans, L. and H. Van Der Auweraer, *Modal Testing and Analysis of Structures under Operational Conditions: Industrial Applications.* Mechanical Systems and Signal Processing, 1999. **13**(2): p. 193-216.

85. Mettemeyer, M. and A. Nanni, *Guidelines for Rapid Load Testing of Concrete Structural Members*. 2001, University of Missouri, Rolla.

86. Saouma, V.E., et al., *Application of Fiber Bragg Grating in Local and Remote Infrastructure Health Monitoring.* Materials and Structures, 1998. **31**: p. 259-266.

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