Technical Report Documentation Page

1. Report No. FHWA/TX-03/1892-1	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle RESEARCH REPORT: INSPECTING FRP COMPOSITE STRUCTURES WITH NONDESTRUCTIVE TESTING	5. Report Date October 2001 6. Performing Organization Code
7. Author(s) Timothy Fowler, Vikram K Kinra, Konstantin Maslov, and Tess J Moon	8. Performing Organization Report No. 1892-1
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, TX 78705-2650	10. Work Unit No. (TRAIS) 11. Contract or Grant No. 0-1892
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, TX 78763-5080	13. Type of Report and Period Covered Research Report 14. Sponsoring Agency Code

15. Supplementary Notes
Project conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration, and the Texas Department of Transportation.

16. Abstract

Structural plastics and composites such as fiber reinforced polymers (FRP) represent a broad class of materials finding increased use in bridge and highway related applications. These materials offer important advantages, including corrosion resistance and formability. A number of bridge-related research and construction projects involving composites have begun at TxDOT and in other states and countries in the recent years, demonstrating the rapidly expanding use and interest in these materials.

As the use of composites is implemented in TxDOT structures, TxDOT must conduct quality assurance testing to ensure structural integrity of the products, much in the same way TxDOT already does with steel and composite structures. Nondestructive testing, especially the acoustic emission method (AE) offers great promise for inspecting FRP structures to ensure integrity. AE testing is used very successfully in quality assurance testing of pressure vessels, and research is needed to adapt this method to the type of composite structures that will be used in highway applications and to consider other methods that might be suitable to structural composites.

This research involved testing of large structural elements to determine the effectiveness of AE and other methods in quality assurance testing of composite structural elements for highways and to develop a protocol for quality assurance testing that could be applied to actual composite members. Damage was induced in these structures so that performance and results could be evaluated under different conditions. Secondary bonds and connections were tested and joints in various locations were evaluated.

17. Key Words FRP composite structures, nondestructive testing	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 148	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Research Report: Inspecting FRP Composite Structures with Nondestructive Testing

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Report Number 1892-1

Inspecting FRP Composite Structures with Nondestructive Testing

in cooperation with the U.S. Department of Transportation, Federal Highway Administration

Research Project 0-1892
Inspecting FRP Composite Structures with Nondestructive Testing

Conducted for the
Texas Department of Transportation
in cooperation with the
U.S. Department of Transportation
Federal Highway Administration
by the
Center for Transportation Research
Bureau of Engineering Research
The University of Texas at Austin

October 2001

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Acknowledgments

The authors express appreciation to Paul McDad, Jeffrey Seiders, Ronald D Medlock, Michael E Smith and others who were instrumental to the project.

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Chapter 1 – Introduction and Overview

1.1 PURPOSE

This report is Research Report Number 1 specified in the Deliverables Table of Texas Department of Transportation (TxDOT) Research Project 0-1892, "Inspecting FRP Composite Structures with Nondestructive Testing." The purpose of the report is to document results of tasks 1, 2, and 3 of the Project Agreement.

1.2 BACKGROUND

The following description was given by TxDOT in the January 7, 1999 Research Project Statement:

> *Structural plastics and composites such as fiber reinforced polymers (FRP) represent a broad class of materials finding increased use in bridge and highway related applications. These materials offer important advantages, including corrosion resistance and formability. A number of bridge-related research and construction projects involving composites have begun at TxDOT and in other states and countries in the recent years, demonstrating the rapidly expanding use and interest in these materials.*
>
> *As the use of composites is implemented in TxDOT structures, TxDOT will need to conduct quality assurance testing to ensure structural integrity of the products, much in the same way TxDOT already does with steel and composite structures. Nondestructive testing, especially the acoustic emission method (AE) offers great promise for inspecting FRP structures to ensure integrity. AE testing is used very successfully in quality assurance testing of pressure vessels, and research is needed to adapt this method to the type of composite structures that will be used in highway applications and to consider other methods that might be suitable to structural composites.*
>
> *This research will involve actual testing of large structural elements to determine the effectiveness of AE and other methods in quality assurance testing of composite structural elements for highways and to develop a protocol for quality assurance testing that may be applied to actual composite members. Damage will be induced in these structures so that performance and results can be evaluated under different conditions. Secondary bonds and connections will be tested and joints in various locations will be evaluated. Consideration of how acoustic emission has been used in pressure vessel work is strongly encouraged.*

TxDOT accepted a joint proposal submitted by The University of Texas at Austin (UT) and Texas A&M University (A&M). The research is being conducted in the Wave Propagation and Damping Laboratory of the Department of Aerospace Engineering at A&M, in the Integrated Mechanics Of Processing and Composites Manufacturing Technologies (IMPACT) Laboratory of the Mechanical Engineering Department at UT, and in the Ferguson Structural Engineering Laboratory of the Civil Engineering Department at UT.

The abstract at the beginning of the Project Agreement between TxDOT, Texas A&M, and UT summarizes the nature and scope of the project. This abstract is as follows:

> *Structural plastics are being considered for use in bridges and other highway structures. These materials are also being used for repair, rehabilitation, and strengthening of existing structures. Experience with pressure vessels, tanks, manlifts, and other applications of structural plastics has demonstrated that initial fabrication quality and periodic nondestructive inspection are important to success.*
>
> *This proposal utilizes complementary strengths of Texas A&M University and The University of Texas at Austin. The objectives of the study are development of test procedures and protocols for nondestructive inspection of structural plastic structures and structural components. Three procedures will be completed.*
>
> *Three nondestructive inspection procedures will be developed:*
>
> - *Global acoustic emission inspection. It is anticipated that this procedure will be used to inspect an entire structure with a single test.*
> - *Local ultrasonic inspection. This procedure complements the acoustic emission procedure and will be used to define the exact location and nature of a defect.*
> - *Visual inspection. The procedure will be based on the existing American Society of Mechanical Engineers RTP-1 Procedure for Reinforced Thermoset Plastic Corrosion resistant Equipment.*
>
> *The procedures will cover inspection of newly fabricated structural members, recently erected structures, and in-service structures. Particular attention will be given to inspection of primary structural members, particularly those that are not easily accessible. The procedures will also include inspection of structural plastics that have been installed for repair, rehabilitation, and strengthening of existing structures.*
>
> *A protocol will specify inspection procedures and scaled models for initial product acceptance and manufacturer and fabricator qualification.*
>
> *A review of ASTM standards will determine if other inspection procedures (visual, penetrant) are required.*
>
> *Field tests will be conducted using prototype field instrumentation.*

1.3 PROJECT SCOPE

The work plan for this project has ten tasks:

1. Conduct literature and database survey and make a critical assessment of current technology.
2. Design, fabricate, and procure test samples.
3. Assemble experimental equipment and conduct preliminary tests.

4. Full scale tests.
5. Develop preliminary test procedures.
6. Conduct field tests of existing composite structural systems.
7. Re-examination of field-test results and optimization of procedures.
8. Design the hardware upgrades for field application of the acoustic emission and ultrasonic technologies.
9. Complete preparation of procedures for inspection of fiber reinforced plastic structures using acoustic emission, visual, and ultrasonic methods, and protocol for nondestructive examination, calibration, initial product acceptance, and manufacturer and fabricator qualification.
10. Preparation of research report and project summary report.

1.4 PURPOSE OF REPORT

This report reviews progress with Tasks 1, 2, and 3 which were scheduled for completion December 31, 2000. The original project proposal submitted by A&M and UT did not include a provision for this report. At the request of the TxDOT Project Director the research report was added to the scope of the project during negotiations leading to award of the contract.

It is important that the procedures that are to be developed as part of this project be practical and suitable for TxDOT use. For this reason, TxDOT guidance and input is an important component of the project strategy. Following completion of the project, TxDOT personnel will be responsible for implementing the procedures in field applications of fiber reinforced plastics (FRP). The researchers have attempted to coordinate their activities with TxDOT to ensure that the specific procedures are in a format that is most useful to the Department of Transportation. The report is intended to serve as a benchmark of project progress and to assist in keeping the Project Director, Project Coordinator, and Project Monitoring Committee appraised of project activities.

1.5 BACKGROUND AND SIGNIFICANCE OF WORK

Structural plastics and composites, particularly fiber-reinforced plastics (FRP) are increasingly being considered for infrastructure applications due to their inherent corrosion resistance. Two structural applications, short span bridge members, and concrete reinforcing bars are being implemented in Texas. Additional properties such as the high strength to weight ratio and the favorable life cycle cost make the materials attractive. The ability to place, form, and fabricate FRP in the field is particularly attractive for repair, rehabilitation and protection of bridges and highway structures. This application is also being implemented in Texas.

FRP materials are experiencing increased use in the civil infrastructure, however, methods to assure structural integrity for both initial product acceptance and long–term reliability are not established. Both new structural members and repair/rehabilitation projects require a means to monitor the quality of the fabrication, installation, and continued structural health.

A composite is a specific type of structural plastic. However, for the purposes of this proposal the terms "structural plastic" and "composite" are used interchangeably. Fiber reinforced plastic (FRP) is the most commonly used composite material.

Complementary TxDOT Projects

TxDOT is actively pursuing the application of composites in four areas. Nondestructive inspection methods that will ensure correct installation and monitor the in-service condition of the composite are essential for confidence in the safety of the application. The four areas of interest are summarized in the following sections a through d.

a. *Primary Structural Members*

Research project 0-1773 entitled "Applications for Composite Materials in TxDOT" has demonstrated the technical feasibility of using FRP materials for primary structural members. The initial goal of the project was to evaluate how composites could be used most effectively in TxDOT structures. The project was originally scheduled for two years. Based on the results achieved, the project was extended by an additional year and the scope of the project expanded to include laboratory testing of prototype short span bridge beams acting compositely with reinforced concrete decks. As a result of this project TxDOT is proceeding with two implementation projects to apply the technology developed.

The first implementation project is for a two-span bridge on FM 3284 near Gregory. Each span is 30 feet long and consists of one-piece contact molded FRP beams and a composite reinforced concrete deck. Funding for a portion of the construction is provided by the U. S. Department of Transportation under its program for innovative bridge construction. The balance of the funds will be provided from state funds. The contract for construction of the bridge has been awarded and construction is expected to begin shortly.

The second implementation project, which is in the design phase, is for a ferry boat landing ramp at Port Aransas. The project will include an FRP structure supporting a grating deck. The grating will be either FRP or steel. Connection details at both the land and water ends of the structure will be the same as the existing steel ramps. This will permit interchangeability between the FRP and steel ramps. Funding is provided by the state.

b. *Repair and Rehabilitation of Deteriorated Reinforced Concrete*

Research Project 0-1774 entitled "Effect of Wrapping Chloride Contaminated Structural Concrete with Multiple Layers of Glass Fibers/Composites and Resin" evaluated the effect of FRP wrap on the rate of corrosion and the structural integrity of a deteriorated structure. Deteriorated samples in both the wrapped and unwrapped condition were subjected to additional corrosive attack and the effect of the FRP wrap evaluated. Emphasis was placed on salt water attack of the steel reinforcement.

A parallel demonstration project is being carried out on a severely corroded bridge in Lubbock, Texas. The bridge was extensively rehabilitated using a polymer impregnated glass fiber wrap applied by a firm that specializes in applying composites for external reinforcement and structural rehabilitation.

c. *Strengthening*

Research Project 0-1776 entitled “Development of Methods to Strengthen Existing Structures with Composites” evaluated the use of high performance carbon fiber reinforced plastics (CFRP) for strengthening existing structures. The objectives of this project were to investigate the effectiveness of composite materials to strengthen reinforced concrete bridges and to develop design guidelines for the safe implementation of these materials in existing bridges. The research demonstrated that carbon fiber reinforced composites are viable means of increasing the flexural strength of reinforced concrete beams. The critical issue of debonding of the composite from the concrete surface depends on a number of factors including the quality of the bond. A second project developed design criteria and application methods for CFRP strengthening of reinforced concrete bent caps.

The TxDOT Houston District Office is implementing the results of the bent cap project in the field. Inspection is primarily visual. Additional methods for periodic in-service inspection are desirable.

d. *FRP Reinforcing Bars*

A demonstration project is using glass FRP reinforcing bars in the reinforced concrete deck of the Sierrita de la Cruz Creek Bridge on highway 1061 near Amarillo. The project is funded by the U. S. Department of Transportation and the state. Performance of the bridge is being monitored by a number of universities.

Research and Development Programs in other States

A number of states are conducting research and implementing demonstration projects of the type being studied in Texas and described above. A list of states that reference composites on their Department of Transportation websites is given in Table 2.2. Details of the references are included in Volume 2 of the electronic version of the literature search that accompanies this report. The researchers are not aware of any projects to develop nondestructive inspections methods being carried out in other states.

A number of states are conducting experiments with composite bridge decks because of the damage caused to reinforced concrete by deicing chemicals. In Texas, this problem is not as severe as in many of the northern states because of the climate. Accordingly, Texas has not conducted research into the use of composite bridge decks. However, the use of FRP reinforcing bars in the Sierrita de la Cruz Creek Bridge is in response to the problem caused by deicing chemicals. In particular situations, such as the Port Aransas ferry boat landing ramp, use of a composite deck may be appropriate.

1.6 OVERVIEW

Plastics are a large, complex, constantly developing group of materials that present the structural engineer with a combination of often unfamiliar and unique advantages and limitations. These synthetic organic high polymers range in strength and stiffness from soft and flexible to hard and rigid. They can be used in their pure unaltered state, they can be expanded into lightweight structural foam, and they can be modified by additives and reinforcements. Typically, a structural composite consists of reinforcing fibers in a polymer matrix. In most cases, the characteristics of the composite are profoundly different from those of the individual components. On a strength-to-weight basis, composites can provide the most efficient structural materials available to the engineer. Conversely, they may easily fail if not properly designed, tested, and employed.

Twelve billion pounds of plastic are used annually in new construction. By far the largest portion is for pipe applications such as, sewer, gas, water, and drainage pipe, ducting, electrical conduit, and bathroom and sanitary fittings. Other construction applications include siding, insulation, flooring, windows and doors, wallboard, prefabricated homes, and security and other types of glazing. None of these uses are classic structural engineering applications. Other engineering disciplines have taken advantage of the unique properties of structural composites and have used them as the principal structural material. In the transportation field, weight is one of the most important considerations, and composites are used to fabricate primary structural members of mass transit vehicles, stealth fighter aircraft, and commercial airliners. Sports equipment such as skis, tennis rackets, golf clubs, and fishing poles are made almost entirely from structural plastics. In corrosive environments of the type found in industry, composite tanks, pressure vessels, and other containers are common.

Experience has shown that periodic inspection is an essential requirement for successful use of reinforced plastics. The history of failures experienced with fiber reinforced plastic (FRP) tanks and pressure vessels in the chemical industry and with FRP manlift crane booms in the electrical utility industry led to development of visual and acoustic emission inspection methods for these structures. Periodic inspection will be required for composite structures. Inspectability of such structures is an important consideration. In addition, determination of critical defect sizes and the relationship of the defect to the sensitivity of the inspection method must be considered. The United States Department of Transportation refers to this as damage tolerance design and requires that the technique be used for design of transportation equipment such as aircraft, tank cars, and intermodal tanks.

Nondestructive detection techniques are required to identify defects that can develop during manufacture, forming, fabrication, installation, or service. TxDOT has suggested the fabrication and construction sequence shown in Figure 1. Quality control (QC) and quality assurance (QA) are required at all stages. In general, material manufacturers accept responsibility for QC/QA of the resin, fibers, bolts, and adhesives. The nondestructive test procedures to be developed under this project will be used for QC/QA of the individual FRP components, the fabricated parts, and the completed structures. Periodic or continuous monitoring of in-service structures is also necessary.

Numerous environmental and human factors contribute to defective installations of FRP materials. Field installation of composites, such as when used for external reinforcement and structural rehabilitation, can lead to these types of problems.

In-service damage is frequently encountered in FRP structures, and it is important to identify this type of damage and to assess its effect on structural integrity. This type of damage can be sudden, as is the case with impact damage, or can take place over a period of time, as is the case with long-term overload, which shows as time dependent viscoelastic creep deformation.

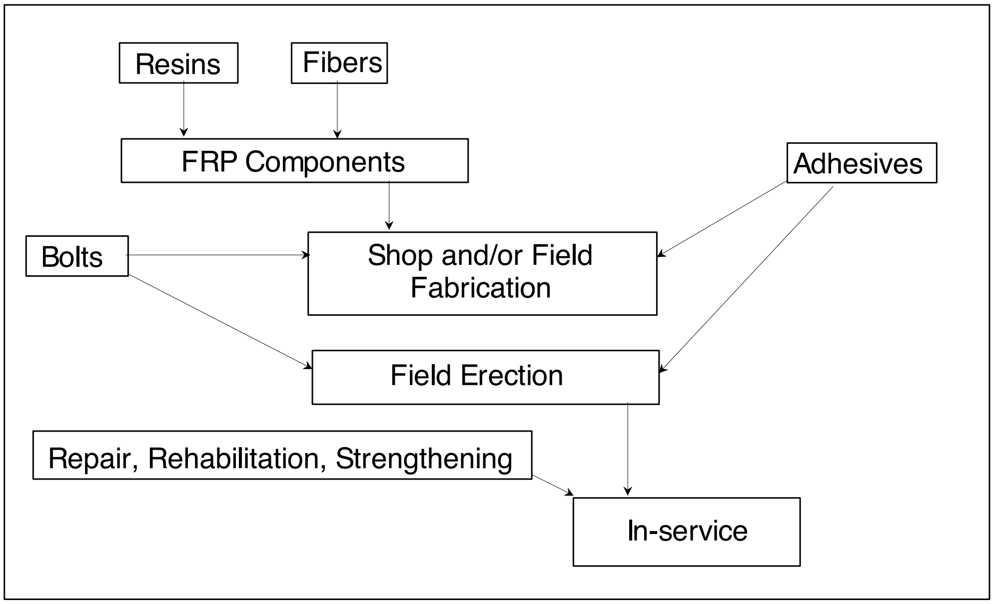

Figure 1.1 - Fabrication and Construction Sequence

Chapter 2 – Literature Review

2.1 INTRODUCTION

This Chapter reports the results achieved on Task 1. The Project Agreement summarizes the task as follows.

Task 1. Conduct Literature and Database Survey and make a critical assessment of current technology.

For this report, emphasis is placed on fiber reinforced plastic (FRP) materials. As stated in the Project Agreement, FRP is the most commonly used composite material and it is anticipated that this type of composite is likely to be widely used in highway structures. Other forms of composite materials, such as mineral reinforced or particulate reinforced, are unlikely to find much use in structural highway applications.

References are listed in the appendices to this chapter and are broken down as described below. This task is essentially complete, however, new literature will continue to be reviewed so that researchers will remain current with this rapidly changing field.

2.2 COMPREHENSIVE LITERATURE SEARCH

A comprehensive literature search was performed. Appendix A to this chapter lists American Society for Testing and Materials (ASTM) standards. Appendix B provides a property map of these ASTM standards. Appendix C lists non-ASTM standards, and Appendix D lists references relating to the use of structural composites in the infrastructure.

The literature search for standards was performed as follows:

- The following keywords were used: Polymer matrix composite, composite, thermoplastic, thermoset, and fiber reinforced plastics.
- The ASTM standards index
- The Information Handling Service Engineering Resource Center, which contains standards from over a thousand notable professional organizations, was searched. The specific organizations of interest were:
  - American Association of State Highway and Transportation Officials (AASHTO)
  - American Road and Transportation Builders Association (ARTBA)
  - American Society of Mechanical Engineers (ASME)
  - American Society of Safety Engineering (ASSA)
  - American Society of Safety Engineers (ASSE)
  - British Standards Institution (BSI)
  - Bureau of Standards Metrology and Inspection – Taiwan (BSMI)
  - Composite Can and Tube Institute (CCTI)
  - Civil Engineering Data/ Dept of the Army (CED)
  - Composites Institute (CIN)
  - Construction Safety Association of Ontario (CSAO)
  - China Standards Information Centre (CSIC)

US Department Of Transportation (DOT)
European Association for Standardizing Information (ECMA)
Federal Highway Administration (FHWA)
Federal Motor Vehicle Safety Standards (FMVS)
Federal Motor Vehicle Safety Standards and Regulations (FMVSS)
Glass Tempering Association (GTA)
US Department of Housing and Urban Development (HUD)
Institute of Electrical and Electronics Engineers (IEEE)
International Standards Organization (ISO)
The Mining and Metallurgical Society of America (MMSA)
National Institute of Building Sciences (NIBS)
National Conference of Standards Labs (NCSL)
PLASTEC, the trade shows for the plastics industry
Plastic Pipe Institute (PPI)
Society of Automotive Engineers (SAE)
Welding Research Institute (WRI)

References in Appendix D were obtained from a variety of sources, including but not limited to: The Engineering Compendex (1970 - present), journal websites, and other Internet searches. Representative keyword combinations were: composite bridge manufacturing and structural composite defects. Additional details of the search strategy are given below.

A search was also made of the website of each state Department of Transportation. Table 2.2 reports which states have documents that relate to composites. Specific references are given in the electronic version of the literature search (See Paragraph 2.2.1)

2.2.1 ELECTRONIC VERSION OF LITERATURE SEARCH

In addition to the references contained in this report, a more extensive electronic version has been provided to the Project Director. Two disks, entitled TxDOT Project 0-1892 Vol. 1 & 2, contain results of the comprehensive searches conducted for this project. The contents of the disks, the search strategies and disk navigation are explained below.

Volume 1:

The Vol. 1 disk contains results of a comprehensive standards search and miscellaneous relevant polymer composite information, including a list of related articles and pictures of failed glass-fabric composite test specimens. This disk includes:

- Standards Review: This folder contains three topics ASTM standards, non-ASTM standards, and properties corresponding to standards.
    - ✓ ASTM Standards: This folder contains over 300 relevant standards organized in a Microsoft Access database. The shortcut takes you directly to the database of standards where you can view the full text via the hyperlink.

Table 2.2 – States that Reference Composites on their Department of Transportation Website

State		State		State		State	
Alabama	No	Indiana	No	Nebraska	No	South Carolina	No
Alaska	No	Iowa	No	Nevada	No	South Dakota	Yes
Arizona	No	Kansas	Yes	New Hampshire	No	Tennessee	No
Arkansas	No	Kentucky	No	New Jersey	No	Utah	No
California	Yes	Louisiana	No	New Mexico	No	Vermont	No
Colorado	No	Maine	No	New York	Yes	Virginia	Yes
Connecticut	No	Maryland	No	North Carolina	No	Washington	No
Delaware	Yes	Massachusetts	No	North Dakota	No	West Virginia	Yes
Florida	Yes	Michigan	No	Ohio	Yes	Wisconsin	No
Georgia	Yes	Minnesota	Yes	Oklahoma	No	Wyoming	No
Hawaii	No	Mississippi	No	Oregon	Yes		
Idaho	No	Missouri	Yes	Pennsylvania	No		
Illinois	No	Montana	No	Rhode Island	Yes		

  - ✓ Non-ASTM Standards: This folder contains the standards that are relevant to composites but from other organizations in an Excel spreadsheet. The shortcut opens the spreadsheet that contains links to detailed information on the standard including the topic, the abstract, and ordering information.
  - ✓ Properties Corresponding to Standards: This folder contains a draft of a list of properties and the corresponding standards for polymer composites.

- Miscellaneous Relevant Polymer Composite Information: This folder contains four documents that are pertinent to Project 0-1892.
  - ✓ Structural Composite References: A list of references concerning defects and issues concerning the manufacturing process of structural polymer composites.
  - ✓ TxDOT Project 0-1774 Failed Specimens: This folder contains photos of our failed glass-fabric composite test specimens.
  - ✓ FRP Equipment Inspection Guide: This folder contains an Inspection Guide for FRP Equipment.
  - ✓ Fabrication Specs of FRP Beams: This folder contains the TxDOT specifications for a FRP bridge over a drainage ditch in San Patricio County.

Volume 2:
The Vol. 2 disk contains results of a comprehensive search of: 1) construction and highway databases; 2) State Departments of Transportation websites; and 3) monotonic and cyclic failure in polymer matrix (or FRP) composites literature. This disk includes:

- Construction and Highway Databases Review: This folder contains the results of a comprehensive Internet search of transportation and civil infrastructure institutions and organizations. The shortcut opens the document that contains the details of the search including links to websites and links to downloaded "pdf" files and documents. Websites not containing any information on FRP composites are labeled with none.

- State Departments of Transportation Review: This folder contains the results of a search of each state DOT website for relevant content. The shortcut opens the document that contains links to each states DOT website and FRP-related articles. State websites not containing any information on FRP composites are labeled with none.

- Task 1e. Failure in Polymer Matrix (or FRP) Composite Literature: This is contained in two folders:
  - ✓ Engineering Compendex: This folder contains the Engineering Compendex search results for relevant literature on monotonic and cyclic failure in polymer matrix (or FRP) composites. The shortcut opens a spreadsheet that has all the related references, the search keywords used, and the links to the downloaded abstract or full-text article.
  - ✓ University Microfilms, Inc. (UMI): This folder contains UMI Search Results for relevant literature on monotonic and cyclic failure in polymer matrix (or FRP) composites. The shortcut to the spreadsheet has the dissertation and thesis related references, the search keywords used, and the links to the abstract or full-text article.

Vol. 1 Search Specifics:
- Standards Review
  The following keywords were used:
    Polymer matrix composite,
    Composite,
    Thermoplastic,
    Thermoset, and
    Fiber reinforced plastics.
  The search included the Information Handling Service (I.H.S.) Engineering Resource Center (http://www.ihserc.com), which contains standards from over a thousand notable professional organizations. The specific organizations searched are: AASHTO; ARTBA; ASME; ASSA; ASSE; BSI; BSMI; CCTI; CED; CIN; CINS; CSAO; CSIC; DOT; ECMA; FHWA; FMVS; FMVSS; GTA; HUD; IEEE; ISO; MMSA; NIBS; NCSL; PLASTEC; PPI; SAE; WRI.
- Miscellaneous Relevant Polymer Composite Information:
  - ✓ Structural Composite References: This includes a number of related articles/documents obtained from a variety of sources, including but not limited to: The Engineering Compendex, Journal websites, and other Internet searches.

Representative keyword combinations were: composite bridge manufacturing and structural composite defects.

Vol. 2 Search Specifics:

- Construction and Highway Databases Review:
  - ✓ The construction and highway database search was conducted on the Internet through search engines. Many sites had internal databases and keyword searches to find relevant content. Keywords searched include: construction, highway, transportation, standards, infrastructure, institution, FRP, fiber reinforced plastic, bridge, repair, and rehabilitation.
- State Departments of Transportation Review:
  - ✓ Each state DOT website was searched for relevant content.
- Failure in Polymer Matrix (or FRP) Composite Literature:
  - ✓ Engineering Compendex: The Engineering Compendex (1970- present) was reviewed for relevant literature on monotonic and cyclic failure in polymer matrix (or FRP) composites. Limited literature is available on composites specifically for the civil infrastructure so the general area of FRP composite failure was reviewed. The specific keywords searched are diagramed in the two tiers below:
    - Fiber reinforced plastic
      - and glass
      - and failure
      - and one of the following set (fatigue, damage, strength)
    - Polymer composite
      - and glass
      - and failure
      - and one of the following set (fatigue, damage, strength)
    - Fiber reinforced plastic
      - and one of the following set (failure, concrete, damage)
      - and one of the following set (thermal, moisture, ultraviolet, environmental degradation)
    - Polymer composite
      - and one of the following set (failure, concrete, damage)
      - and one of the following set (thermal, moisture, ultraviolet, environmental degradation)
  - ✓ University Microfilms, Inc. (UMI): The University Microfilms, Inc. (UMI), www.umi.com, was reviewed for relevant literature on monotonic and cyclic failure in polymer matrix (or FRP) composites. Limited literature is available on composites specifically for the civil infrastructure so the general area of FRP composite failure was reviewed. The specific keywords searched are diagramed in the two tiers below:
    - Composite
      - and failure
      - and one of the following set (damage, glass, moisture, thermal)
    - Composite
      - and fatigue
      - and glass

Composite
    and concrete
    and damage
Composite
    and strength
    and glass
Concrete
    and failure
    and thermal
FRP
    and concrete
    and one of the following set (thermal, failure)
FRP
    and glass
    and one of the following set (failure, fatigue, strength)
FRP
    and carbon
    and one of the following set (failure, polymer, strength)
Polymer
    and carbon
    and composite
Polymer
    and glass
    and one of the following set (failure, fatigue, strength, composite)

2.3 NONDESTRUCTIVE INSPECTION OF COMPOSITE STRUCTURES

Unless footnoted to the contrary, references in this section are given in Appendix E of this Chapter.

The literature reports a large number of nondestructive test (NDT) and inspection techniques for composite structures. Many are relevant to TxDOT applications. Approximately, 150 articles reporting development of a new inspection technology or improving application of an existing technology for particular type of composite are published annually. At the same time, however, very little development has been done of NDT techniques used specifically for inspection of composite highway structures or composite materials used in such structures [1]. This can be explained by the fact that use in transportation related structures is a relatively recent application of composites. A second factor is the inhomogeneity of composite material, which makes nondestructive inspection extremely challenging.

In order to develop NDT techniques for highway structures, it is useful to borrow as much information as possible from existing inspection methods for FRP structures. Defects in composites may be due to several factors including improper design, fabrication and manufacturing, and service induced damage. Design defects include improper number of fibers, incompatible resin, and inappropriate stress concentrations. Fabrication and manufacturing defects include concealed cuts, knots, lack of rovings, resin starved layers, and improperly cured resin. Defects that develop in-service include cracks, matrix micro-cracks, fiber breakage, fiber/matrix debonding, and impact damage. The latter often shows as delamination and large matrix cracks. Correspondingly, different techniques must be used for different types of damage detection.

An overview of the most frequently used NDT techniques for the inspection of composites is presented in Table 1. It is important to observe that most of the NDT methods that are used for inspection of metal parts are of very little use for inspection of composite materials of the type used in civil engineering structures. A comprehensive review of inspection techniques suitable for polymer matrix composites can be found elsewhere [2-6]. In general, these methods can be classified into destructive and nondestructive evaluation (NDE) techniques. The techniques based on destructive evaluation include the de-ply technique and cross-section fractography, while among the non-destructive ones are visual inspection, radiographic imaging, and ultrasonic techniques.

Destructive techniques

There are two major techniques that have been used extensively for characterization of composite damage: the de-ply technique and cross-section fractography. The de-ply technique involves pyrolysing the matrix resin in a furnace so that the plies of a laminate can be separated. Gold chloride, sodium sulphate and calcium oxide are used as the penetrant [9-11], or a release film is inserted along the interply edges [12] to facilitate easy de-ply after the pyrolysis. The de-ply technique is often combined with radiographic imaging techniques to obtain the images of ply-by-ply delamination [13,14]. The results from the de-ply technique are considered to be quite reliable, and thus have often been used to benchmark non-destructive techniques.

Another approach to produce detailed three-dimensional maps of impact damage consists of sectioning the laminate at different locations and different orientations through the whole damage zone [15,16]. Microscopic observation and fractography of the cross-sections are used to evaluate the spatial distribution of the damage.

The disadvantages of destructive techniques are that they are time-consuming; they expose only a limited view of the laminar interfaces, and they can introduce additional damage during sample preparation. As a result, use of destructive techniques is usually limited to development of new composites or as a control method for nondestructive inspection techniques.

Nondestructive techniques

a. *Visual inspection.*

Visual inspection is the primary method of inspection for structural composites. The method is inexpensive and fast. It is recommended that visual be used as the initial method of inspection. It is an excellent technique for detecting obvious surface defects. Unfortunately, visual inspection cannot be used as a stand-alone method of inspection for structural FRP. There are a number of drawbacks to the method including its inability to detect some types of internal delaminations and cracks, the difficulty in using it for painted composites or for FRP materials with poor surface quality, and its inability to detect missing reinforcement. In an opaque material, the method is limited to detection of surface defects. In other materials such as graphite fiber and hybrid composites or composites with weathered surfaces where the surface has lost the resin in the surface layer due to environmental attack the method cannot be used. As part of this project, a test procedure for visual inspection of FRP highway structures will be developed. Evaluation criteria for visual inspection of FRP tanks and pressure vessels are given in ASME RTP-1 [5][1] and Section X of the ASME Code [4][1]. These criteria will be used as a basis for establishing evaluation criteria for FRP highway structures.

Many composites, such as polymer matrix composites reinforced with glass fibers are translucent. For these materials, defects and damage can be evaluated with the aid of strong transmitted light [17,18]. Opaque materials such as carbon and graphite reinforced FRP, thick sections of some translucent materials, and painted materials cannot be inspected with transmitted light. Hirai et al. [18] quantitatively characterized the shape and area of impact damage in glass woven fabric-vinyl ester laminates using an optical stereo microscope. Although it is very easy to generate the images with this technique, a major disadvantage is that the depth profile of internal damage cannot be obtained accurately.

b. *Dye Penetrant*

Dye penetrant is used to highlight cracks and improve the contrast between defects and the underlying material. The literature review shows that existing procedures are for dye penetrant inspection of metals and are not directly applicable to composite materials. In view of this, and recognizing that the technique works well for composite materials, a dye penetrant inspection procedure for composite materials will be developed as part of this project. This procedure was not included in the original Project Agreement but has been added as a result of the critical technology assessment carried out under task 1.

c. *Radiographic imaging techniques*

In conventional high-energy radiation radiography, such as X-ray, the overall image of internal features is recorded following the transmission of an X-ray beam through a specimen. Therefore, any defects or damage present within the specimen are superimposed on a two-dimensional (2D) image, without any indication of the depth of the flaw. This makes assessment of details of internal damage, such as microcracks and delamination, impossible. There are various radiographic techniques that have been developed in recent years to obtain detailed three-dimensional images of internal damage. These include X-ray computed tomography [19], neutron tomography [20], Compton backscatter technique [21], and stereo radiography [22]. The difficulty in resolving the damage in the two-dimensional image is a problem shared by all radiographic techniques. In many cases, it is necessary to determine the nature of the damage area with a destructive procedure such as drilling a hole at the center of the flawed area.

Radiography has been widely used for metal inspection. Resolution of cracks is not as good with structural plastics as with metals because of the much lower density. An important advantage of radiography is the permanent record that is obtained. Disadvantages are the cost, time required, and the need to access both sides of a component. One of the biggest problems with radiography is the safety. This issue can be managed, with proper training and strict control. However, it is

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[1] See Appendix F for this reference

often necessary to evacuate people from the immediate area, which in the case of a highway structure might lead to a disruption of traffic flow.

d. *Electromagnetic techniques*

Electromagnetic based inspection methods include eddy current [23], dielectric spectroscopy [24, 25], microwave scattering [26], nuclear magnetic resonance tomography [27], and electromagnetic ultrasonic technique [28]. Glass reinforced FRP material are not conductive and eddy current and the electromagnetic ultrasonic technique, which are based on excitation of Foucault currents in a conductive material, have very limited application. It is possible to use the methods with some carbon or graphite reinforced materials. However, the sensitivity is limited by the low conductivity of FRP at low frequency. Application of dielectric spectroscopy can find its use in highway related composite structures to measure moisture penetration in adhesively bonded composite structures and thus to monitor the degradation of adhesive joins. Nuclear magnetic resonance tomography is simply too complex, expensive, and slow to be used for routine inspection.

e. *Optical methods*

Electronic speckle pattern interferometry (ESPI) uses intensity fringe patterns to evaluate delaminations, cracks and other defects in glass-fiber reinforced panels [30-32]. Since defects in objects usually induce strain concentrations, shear ESPI reveals defects by identifying anomalies in strain concentration. Laser shearography [33-36], based on the same principle, also uses different optical method of strain detection. Both techniques have been successfully used during initial manufacture and for inspection and qualification of repairs. Both methods offer a rapid and unique inspection for the NDT of composite components. At the present time, these methods have only been used in a laboratory environment because of their complexity and sensitivity to external noise and vibration. In general, the inhomogeneity of composites used in civil engineering limits the application of optical techniques. In certain unique cases, such as thermal damage, selected optical techniques such as laser induced fluorescence imaging can provide quick and reliable information about the state of damage [37]. It is unlikely that optical techniques will find wide application as an NDE method for inspection of composites.

f. *Thermography*

Thermography was found to be comparable to C-scan when testing for near-surface defects and can therefore be used in preference to C-scan. It has the additional advantages of on-site testing, increased speed, and in that it is a remote testing procedure [38-41]. Pulsed infrared thermographic inspection has proven to be a fast, accurate, reliable and cost effective NDE alternative to traditional ultrasonic NDE of commercial aircraft structures. [42]. The inspection method, which is based on the temperature turbulence that appears on the sample surface due to the thermal insulation of the defect, has been effective for identifying delamination defects in carbon fiber reinforced plastics [39]. Lock-in thermography is the more powerful technique of detecting impact damage, while transient thermography is more suitable for detecting inclusions. Thermal non-destructive testing is up to 30 times quicker than underwater ultrasonic C-scanning and may ultimately provide a solution to the problem of rapid quantitative in-service and manufacturing process inspection of commercial aircraft components [40]. It can be used for inspection of thick composites [43], although, the ability of the line-scanning system to detect defects in the carbon fiber reinforced composites is generally limited to a depth of 0.5 mm [38] because of the low thermal conductivity of FRP. The technique is very promising for inspection of concrete civil engineering structures that have been reinforced or rehabilitated with composite materials [44]. In this case, due to relatively high thermal conductivity of concrete, thermography was successful in detecting both simulated and actual disbonds in several types of composite reinforcements.

Thermography will be evaluated experimentally as part of this project. Advantages are that indications are directly related to the damage and that the inspection can be conducted from a distance without contact with the structure. The primary disadvantages are the slow speed and the limitations caused by the low thermal conductivity of FRP materials. The latter problem limits the depth and type of defect that can be detected.

A new hybrid ultrasonic/infrared technology makes use of a short single pulse of ultrasound to cause cracks to heat up and become visible in the infrared region. Wherever cracks, disbonds, delaminations or other defects are present, the sound field causes the defect to heat locally. This technique is applicable to large and irregularly shaped objects [45]. The applicability of the method was proven with several polymer and composite samples having delaminations, impact damages, voids, and inclusions [46]. Examples are presented showing the detection of defects in thick composite materials [47]. However, ultrasound application requires access to the testing surface and point to point scanning. This makes it nether fast or remote, thus negating some of the advantages of the method.

g. *Mechanical vibration*

These methods include mechanical impedance analysis (MIA) [48], which is widely used for detecting debonds in multilayer structures made of advanced composites, delaminations in plastics, and some other defects. In tested objects, bending waves of sonic and low ultrasonic frequencies are excited and input impedance at a point of application is measured. This is a qualitative method suitable only for near surface defect detection. A variant of MIA is the acoustic impact technique that measures input impedance by reaction of the media during impact [50]. It was successfully tested for NDE of graphite/epoxy and graphite/phenolic composites. It is easy in application, but has all the limitations of MIA.

A different approach is taken by modal testing [49], where change of dynamic behavior (frequency, mode shapes, amplitude, and phase) due to structural damages is measured. This method is limited to quick detection of very big damage, but is very useful for this specific application.

h. *Embedded sensors.*

A method that is often related to the mechanical vibration NDE techniques is mechanical static or dynamic (vibration or ultrasonic) NDE with the use of embedded sensors. Typically the sensors are used to measure strain or static deformation [51], or for dynamic testing [52] or sensing of echoed ultrasonic signals [53,29]. However, because optical fibers are always an order of a magnitude bigger than material fibers, stress concentrations will inevitably be created, which can in turn can lead to premature damage initiation. These systems, designed primarily for condition monitoring rather than defect imaging [7], have proved to be capable of detecting small (centimeter square) delaminations, millimeter-sized holes and impact damage of a few joules and are in an early stage of development.

Another unrelated type of embedded sensor is a short wave-guide ultrasonic probe that is embedded in the composite for in-situ cure monitoring [8]. The sensor responds to changes in resin density and sound velocity during cure and can be quantitatively calibrated for determination of the final cure to help to produce higher quality composites. In some respects, this is not an NDT technique.

i. *Acoustic Emission and Ultrasound*

Details of these methods are discussed in Sections 2.4 and 2.5 of this chapter.

j. *Other acoustic techniques*

There are several non-traditional NDE techniques that involve elastic wave propagation in composites, but all of them have very limited area of application, or they simply cannot be backed by well-understood theory. Acousto-ultrasonics [54,55] has found application as a tool for inspection of adhesive bond strength in composites. It is based on energy (instead of amplitude) approach to elastic wave propagation. Transducer excites an ultrasonic pulse that is allowed to reflect from sample surfaces until noise-like diffusive wave is established. The amplitude and spectral content of it serves as a measure of interface quality. However, object shape can equally influence amplitude of diffusive wave. Moreover, only empirical approach with precise calibration is proposed. That makes acousto-ultrasonics not reliable enough for inspection of highway composite structure elements.

Tapping sound analysis was used for long time as a qualitative method of inspection. With the progress in computation methods numerical simulation of impact sound and feature extraction scheme allows the impact sound to be used in the identification of damages of laminated composites [56]. One of the possible applications of this technique in highway related problems could be inspection of adhesive joints. In absence of adhesion flexural resonance of composite adherent must be easily distinguishable.

No single non-destructive testing (NDT) technique or method is satisfactory to fully assess the structural integrity of a material. Indeed, each method presents some limitations in terms of defect detection and characterization. Additionally, poor signal-to-noise ratio may make signal interpretation complex or unreliable. For these reasons, the concept of NDT data fusion - based on the synergistic use of information from multiple sources in order to facilitate signal interpretation and increase defect detection and characterization - is expanding rapidly [57]. Several well-established and recognized data fusion processes, based on statistical and probabilistic algorithms, were used to combine data. It is shown that, in certain cases, NDT data fusion at pixel level may be adequate to increase knowledge about defect location and characterization and to reduce ambiguity [58]. Data fusion offers the potential of significantly improving the confidence in NDT measurements and inspection techniques and increasing the cost-effectiveness of asset integrity management.

Table 2.3 - NDT Techniques for Flaw Detection And Characterization Of Composites.

NDT Techniques	Features	Applicability to composites	
		STRENGTH	**LIMITATIONS**
Ultrasonics: thickness gauging detection and mapping of delaminations attenuation and velocity measurements polar back-scattering crack detection crack detection using shear-wave ultrasonics	**R,G,C,S** **G,C,S,D** **C,N** **G,C,S,D** **S,I,D**	easy to interpret, convenient high contrast and reliability detects early stage of damage, detects transverse cracks, enhanced sensitivity	material loss is rare in plastic composites; requires point to point inspection, limited in depth due to attenuation; indirect, limited by high variation of composite properties; low contrast due to high attenuation and scattering in composites; low contrast due to high attenuation and scattering in composites; slow
Acoustic emission	**C,S,I**	directly relevant to damage	requires application of load. Does not define type of defect or exact location.
Dye penetrant test	**P,I**	direct, inexpensive	can not work for internal cracks and delaminations, qualitative
Eddy currents: crack detection	**D,G,C,S**	non-contact, convenient	limited to electro conductive graphite fiber composites
Mechanical impedance: disbond detection in some instances	**C,S,G,I,D**	works for low quality material	limited to major disbonds between composite panel and structure
X-radiography: material loss and crack detection low-kV to detect chemical changes penetrant-enhanced X-ray for cracks	**T,P,G,D** **R,G,D** **P,T,G,D**	high resolution and sensitivity; directly relevant to damage	material loss is rare in plastic composites; low contrast for cracks very expensive; very slow, requires access to both sides of the structure; harmful.
Neutron radiography: to detect products of chemical reaction	**T,G,D**	directly relevant to damage	requires heavy equipment, very expensive, very slow
Visual methods: eyeball D-sight for imaging quilting around defect	**D** **P,T,G,I,D**	cheap, convenient fast, remote, sensitive	cannot detect material degradation and internal cracks and delaminations; indirect, works only for good quality surface finish and thin laminates
Thermography: transient thermography to detect disbonds cyclic thermography to detect fatigue	**T,G,I,D** **T,G,I,D**	fast, remote directly relevant to damage	limited by low thermo-conductivity of plastics very slow, requires cycling loading
Optical methods: holography, interferometry, shearography	**P,G,I,D**	fast, remote	requires heavy equipment, hard to interpret for low quality composites

Key:
R = processing image gives quantitative into; G = can produce a scaled Graphical image; C = can be mapped using a Computer-based system; T = can produce a TV type of picture; P = can produce a Photographic type of image; S = can be used as a Single-point technique; I = NDT specialist Interpretation necessary; D = Dimension of damage is the only quantitative into; N = quantitative information Not available.

k. *Summary and conclusions*

Table 2.3 summarizes the features, strengths, and limitations of the NDT methods discussed above.

A large number of nondestructive inspection techniques have been used for laboratory inspection of composites. Unfortunately, many of these methods are unsuitable for field inspection of FRP highway structures. Field applications pose a special set of problems and there are a number of reasons why techniques that work well in the laboratory cannot be used in the field, or even a manufacturing facility. Some methods use complex, expensive equipment that must be used in a controlled laboratory environment. An example is the imaging and tomography equipment used for medical examinations. Other methods are used for a single specific purpose and are not suitable as a general inspection technique. An example is acousto-ultrasonics, which is used to measure bond strength. Some cannot be used without major traffic disruption, or require highly skilled operators. Others methods are only suitable for small objects that can be immersed in a tank of water. Some techniques are very slow and are uneconomical for field use on large structures. Other methods need access to all sides of a structural member.

The following NDT methods show promise for field inspection of FRP components and structures used in TxDOT applications:

a. Visual inspection
b. Dye penetrant enhanced visual inspection
c. Thermography
d. Acoustic emission
e. Ultrasound

For detection of non-surface defects in sections thicker than ½'' the methods are limited to acoustic emission and ultrasound. Test procedures and specific acceptance criteria will be developed for the methods a through e.

2.4 REFERENCES RELATING TO ACOUSTIC EMISSION

References in this section are given in Appendix F of this Chapter.

The initial literature search was conducted at the Department of Defense Nondestructive Testing Information and Analysis Information and Analysis Center (NTIAC). Texas Research Institute, Austin, Texas operate NTIAC. A list of research paper titles involving acoustic emission (AE) in composite materials was obtained. Copies of many of the papers were available through NTIAC or the Engineering Library of the University of Texas at Austin. Relevant papers listed in the NTIAC database, but not available in Austin, were obtained through University of Texas interlibrary exchange. Additional papers from the university library system and the researchers' own files supplemented the NTIAC search. The Committee on Acoustic Emission from reinforced Plastics (CARP) has sponsored six International Symposium on Acoustic Emission from Composite Materials. Papers from these symposia are particularly relevant to this project [86-91].

A review of standard AE test procedure is an essential component of the literature review [1-11]. Knowledge of existing AE test procedures and methods of damage evaluation are essential to development of an AE test procedure for composite structures. The following are considered to be extremely important:

- The existing and proposed recommended practices for AE evaluation of fiber reinforced plastic tanks and vessels prepared by the Committee on Acoustic Emission from Reinforced Plastic (CARP). These documents represent established practice and the state-of-the-art inspection of FRP components.
- Association of American Railroads Procedure for Acoustic Emission Evaluation of Tank Cars. These two procedures are accepted under Federal Railroad Administration rules for inspection of tank cars.
- The MONPAC system. MONPAC is an acoustic emission based system for evaluating the structural integrity of metal tanks and pressure vessels. This procedure has worldwide use, particularly by the petrochemical industry, and has become an important safety tool for all process industries.

More than 350 research papers have been obtained so far. A critical assessment of the AE technique has been undertaken to determine the advantages and disadvantages of the method. The results of the literature search given in Appendix F are grouped under the following headings:

i. National Standards and Codes [1-11]
ii. Relevant ASTM Standards [12-20]
iii. Additional References referred to in this section [21-27]
iv. Data Analysis Based on Acoustic Emission Parameters [28-52]
v. Analysis of Failure Mechanisms in Fiber Reinforced Plastic [53-56]
vi. Data Analysis Using Neural Networks and Pattern Recognition 57-63]
vii. Acoustic Emission Applied to Full-Scale Composite Structures [64-67]
viii. Data Analysis Based on Acoustic Emission Wave Forms from Wide Band Sensors [68-74]
ix. Data Analysis Based on B-Value [75-80]
x. Miscellaneous [81-85]
xi. General References [86-91]

Appendix A is a comprehensive listing of all ASTM standards. For completeness, specific standards directly relevant to the acoustic emission portion of this research are also included in Appendix F.

a. *Overview*

Acoustic emission is an important tool for assessing the structural integrity of process industry equipment. Over the past twenty years it has developed into a reliable, cost effective indicator of structural problems, and is now viewed as a mature technology. The method is used extensively in the utility, petrochemical, and other process industries [21, 22] as an acceptance test for new equipment and as an in-service nondestructive examination technique for pressure vessels, tanks, tank cars, and aerial personnel devices (also known as manlifts or cherry pickers). AE has been found to be a reliable, cost effective indicator of a structural problem and has developed into a mature technology. As discussed later, in the chemical industry use of AE has led to a significant improvement in equipment performance [26,27]. The unique characteristic of AE as a noninvasive global test makes it particularly valuable. As such, it is complementary to other nondestructive examination methods that are used for follow-up local inspection.

The public expects bridges public highways to be safe and not endanger the safety of individuals. In order to meet the public's expectations, bridge members must be structurally sound and maintained in this condition. This is further reinforced by government regulation. Over the past twenty years, the development and introduction of new technologies has resulted in better inspection, fewer failures, and safer operation. Acoustic emission is one of the most important new nondestructive structural integrity inspection methods.

b. *Acoustic Emission.*

Acoustic emission is the elastic energy released by materials when they undergo deformation [21]. Rapid release of this energy results in transient elastic waves that propagate through the material. These waves, which are referred to as stress waves, radiate out from the source and are detected by sensors mounted on the surface of the material. Normally, resonant piezoelectric sensors are used to detect AE. When a stress wave strikes the face of the sensor, the pressure on the crystal causes an output signal. If the signal rises above a preset threshold of detection, the transient signal is referred to as a "sensor hit". Key parameters associated with each hit are measured and recorded by the AE test instrument.

Typically, modern AE instruments record hits by channel number and measure amplitude, duration, signal strength (or MARSE), and hit arrival time. Signal strength is the area under the signal envelope and has units of volts-sec. MARSE is an acronym used in the ASME Code [3] that stands for "Measured Area of the Rectified Signal Envelope". MARSE is often used in place of signal strength. AE tends to occur in bursts, which show as a number of separate sensor hits within a short period of time. This phenomenon is sometimes referred to as a cascade or waterfall. The cascade of hits is, in itself, a signature, and different cascade patterns are characteristic of different types of defects. The emission burst is similar to records of certain types of earthquakes, but occurs over a much shorter time period. The early hits are precursors to the main energy release. The hits at the end of the burst are aftershocks with lower energy content.

c. *Fiber Reinforced Plastics*

Acoustic emission is second to visual inspection as the most widely used nondestructive examination method for fiber reinforced plastic (FRP) equipment. Use of AE for inspection of FRP equipment was begun in the mid 1970's and a series of test procedures were developed by the Committee on Acoustic Emission from Reinforced Plastics (CARP) operating under the auspices of the Society of the Plastics Industry. In 1982, the CARP recommended practice for testing tanks and vessels [23] was published. This was followed in 1983 by the CARP recommended practice for FRP piping systems [24].

As experience has been gained with the use of AE for testing FRP equipment, additional codes and standards have been published. Of these, the American Society of Mechanical Engineers (ASME) Code requirement for mandatory AE testing of FRP pressure vessels [3,4], the

American Society for Nondestructive Testing procedure for balsa core highway tankers[7] and the various ASTM procedures [16,17] are particularly significant. All of these codes, standards, and recommended practices are used for the purpose of detecting defects, flaws, or damage. Experience has shown AE to be a reliable nondestructive examination method for use with FRP equipment.

In FRP, AE is caused by cracking of the matrix, debonding of the matrix from the fibers, laminate separation, fiber pullout, and fiber breakage. AE may also result from viscoelastic flow of the matrix. However, this source is very low energy and is not detectable with the gains and thresholds commonly used for field testing. Stress waves caused by fiber breakage are generally high energy and the resulting sensor hits are large amplitude, high signal strength. In contrast, hits caused by matrix cracking and fiber debonding have low amplitude and low signal strength. Delamination tends to show as long duration, medium amplitude hits, rather than short discrete hits. Examination of the AE data provides the inspector with an understanding of the underlying mechanism causing the AE. Different types of defects will give rise to different combinations of basic mechanisms such as fiber breakage, fiber debonding, and resin cracking. Accordingly, specific defect types will have unique AE signatures [25].

Not all emission is genuine and the ability to distinguish genuine from false emission is a key issue in an acoustic emission test procedure. False emission can arise from a number of sources including mechanical rubbing, a leak, fluid flow, turbulence, wind-induced movement of the cables and sensors, rain, sleet, snow, and thermal expansion due to sun. False emission due to sliding at supports is a common problem. The temperature and load changes during a the test cause dimensional changes and this, in turn, results in sliding and spurious emission

Defects that develop in-service cause strain concentrations. If the local strain caused by the defect exceeds the threshold emission strain, emission will occur. The higher the strain, the greater will be the total emission and the lower the load at onset of emission. The stress concentration at a defect magnifies the local stresses in that area of the vessel. A defect in a high stress area of a vessel will cause higher stresses and result in more emission, than a similar defect in a low stress area. From a structural viewpoint, a defect in a high stress area is more severe than the same type of defect in a low stress area. An acoustic emission test reflects this difference.

Under the same conditions of tensile and flexural stress, defects that cause a high stress concentration will give rise to more emission than defects that cause a low stress concentration. Accordingly, cracks and crack-like defects, such as lack of fusion and incomplete penetration, will be more easily detectable and appear as more severe than defects with low stress concentration factors such as small closed cell porosity, inclusions, and overall thinning. An acoustic emission test provides a measure of the structural significance of a defect because the emission from defects in high stress areas, and from defects that give rise to high stress concentrations is greater than from defects in low stress areas and from defects which give rise to low stress concentrations. The level of emission from many types of defects will depend on the orientation of the defect to the stress field. The greater the strain, the greater will be the emission.

d. *Test Loading and Specimen Size*

For a valid acoustic emission test, stresses in the equipment under test must be increased. Without an increase in stress, acoustic emission will not be stimulated. As far as possible, the direction and distribution of stress due to the test load should be similar to the in-service direction and distribution of stress.

It is very difficult to use laboratory data to develop quantitative measures of emission sources in full-size structures. This was one of the principal reasons why the early promise of acoustic emission was not fulfilled as rapidly or as easily as had been expected. AE analysis techniques such as time of arrival source location, rise time analysis, sensor and array lockouts, guard sensors, frequency analysis, use of long hit definition times, and quantitative b-value analysis, cannot be transferred directly from the laboratory to the field. In laboratory specimens, reflections within the specimen are a major problem and distort the waveform. As a result, laboratory data are not representative of data from full-size structures. Another difference between field and laboratory test data is the distance of the sensor from the source of emission. In the field, the sensor is likely to be much further from the source than on a laboratory test specimen. This distance has a big influence on the initial portion of the signal. As the wave travels through the material, different frequency components will travel at different speeds, causing spreading of the wave. As a further complication, high frequency components will be attenuated more than low frequency components. This will also modify the wave shape.

e. *Felicity Effect and Felicity Ratio*

Classical acoustic emission theory states that if a material is loaded, unloaded, and reloaded, emission will not occur until the previous maximum load is reached. This phenomenon is known as the Kaiser effect. If significant damage is present in an FRP structure, or if the laminate is overstressed, the Kaiser effect breaks down and emission occurs below the previous maximum load. This is known as the Felicity effect and is one of the most important tools for assessing the structural significance of acoustic emission data. The Felicity effect becomes more pronounced the more severe the damage or overstress. The Felicity ratio is defined as the load at onset of emission compared to the previous maximum load and is often used as a key indicator of significant structural defects. Major structural defects in FRP materials exhibit a pronounced Felicity effect.

f. *Sensor Positioning*.

Sensor locations are chosen so that a structural defect at any point on the structure can be detected. Sensors are also placed at joints, at areas of high stress, and at areas that historically show problems. The sensor spacing depends on the attenuation of the item under test. Accordingly, structures with coatings that attenuate the signal require sensors to be more closely spaced than structures that are uncoated. Some types of insulation systems, particularly those bonded to the surface of the structural member, also attenuate the signal.

g. *ASME Code*

For many years, Section X of the ASME Code has required qualification of all vessel designs by cyclic and burst testing of a prototype. The qualification procedure requires 100,000 pressure cycles from atmospheric pressure to design pressure and back. The cyclic test is followed by a burst test to at least six times the design pressure. For one-of-a-kind vessels, this procedure is prohibitively expensive, necessitating a minimum of two vessels in order to obtain one serviceable vessel. In the 1980's, Subcommittee X of the ASME Code addressed this problem and developed new design, fabrication, and test procedures for one-of-a-kind vessels. Section X refers to this type of vessel as a Class II vessel, and the new procedures include mandatory design rules and acceptance testing by acoustic emission. In part, the rules are based on experience at Dow Chemical, Freeport, Texas where FRP pressure vessels have been used successfully for a number of years. Experience with design and AE testing of high pressure downhole tubing, atmospheric storage tanks, line piping, and the CARP recommended practices [6,24] also provided base data for the Section X provisions.

Evaluation Criteria. Article RT-6 of Section X lists evaluation criteria. An acceptable vessel must meet criteria based on the following:

i. Emission during pressure hold.
ii. Felicity Ratio.
iii. Total counts.
iv. Large amplitude hits.
v. Long duration, high signal strength (or MARSE) hits.

First and Subsequent Loading. Nonstructural emission is often observed when an FRP component is initially loaded. This emission is due to cracking of excess resin and redistribution of micro-fabrication stresses. Subsequent loadings will be much quieter, and only significant defects will emit. To take account of this phenomenon, different criteria are used for first and subsequent loading.

h. *Tank and Pressure Vessel* Application.

The first large successful application of AE inspection was for FRP tanks and pressure vessels. In 1978 the Committee on Acoustic Emission from Reinforced Plastics (CARP) was formed under the auspices of the Society of the Plastics Industry, Inc. (SPI). The cooperative efforts of a number of chemical companies, fiberglass equipment fabricators, materials suppliers, instrument manufacturers, and academic and research institutions led to development of the CARP Recommended Practice [23]. In North America, the excellent results achieved with this recommended practice led to use of acoustic emission in the American Society of Mechanical Engineers (ASME) Code [3,4].

In the chemical process industry, the early performance of FRP pipe and vessels had been poor, and numerous failures occurred. Apart from acoustic emission, there is no satisfactory test for determining the structural adequacy of FRP equipment. Accordingly, the technique has filled an important need, and development and application of the technology has been rapid.

Figure 2.1 shows catastrophic FRP tank failures of Monsanto Company vessels during the period 1972-91 [22]. The rate of more than two per year experienced during the 1970's is clearly unacceptable. These major failures were accompanied by numerous minor failures such as leaks, cracks at nozzles, breakage of holdown lugs and attachments, internal surface cracking, and blistering. As a result, many tanks became unsuitable for their intended function.

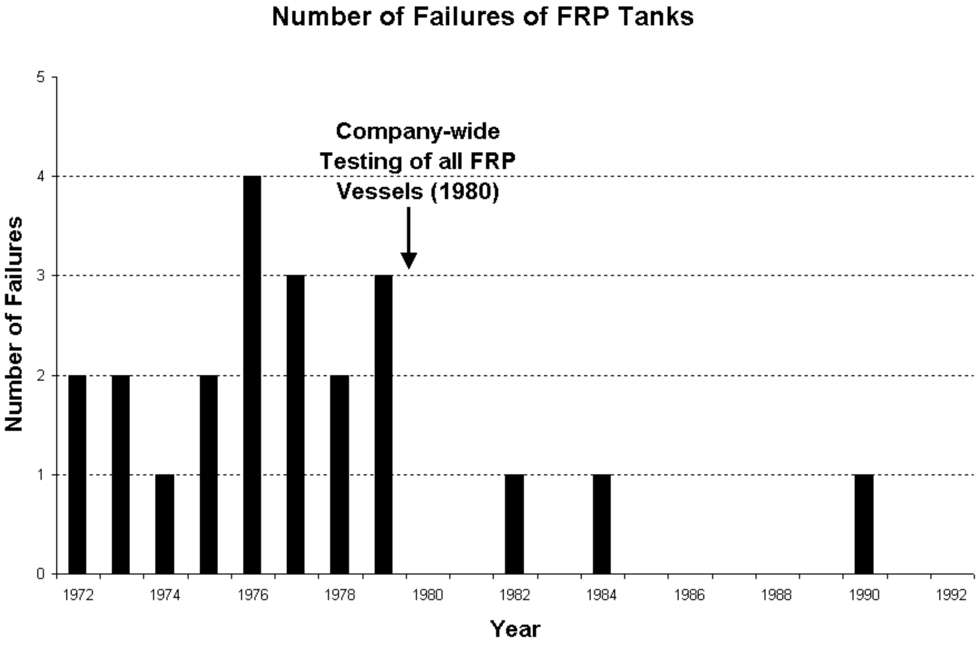

Figure 2.1 – Catastrophic Failures of FRP Tanks at Monsanto Company, 1972-92 [22]

The reasons for this poor performance are varied. They can, however, be covered by the general categories of: inadequate design; variability of fabrication quality; transportation, handling, storage, and installation damage; in-service abuse; and corrosion attack. As noted previously, the lack of an adequate test method for FRP permitted defects to go undetected until they had reached serious proportions. The dramatic reduction in catastrophic failures shown in Figure 2.1 corresponds to implementation of company-wide acoustic emission testing in 1980. Other factors, such as improved design methods, better control of fabrication quality, and a greater understanding of the nature of composites, also contributed to the reduction in failures.

The 1982 and 1984 failures occurred in tanks that had undergone acoustic emission testing. In both cases, the test showed the tanks were likely to fail under continued operation and, in one case, a replacement tank had been ordered. Both tanks were operated at reduced levels and appropriate precautions had been taken to mitigate the consequences of failure. A wind borne object striking the tank during a gale caused the 1990 failure. Obviously, acoustic emission is not able to help with this type of problem.

2.5 REFERENCES RELATING TO ULTRASOUND

Unless footnoted to the contrary, references in this section are given in Appendix G of this Chapter.

Most reviews of nondestructive evaluation (NDE) techniques agree that that ultrasound is the most sensitive method for detecting damage of polymer matrix composite materials [1-6][2]. Among other methods, stimulated shearography and thermography are named as sensitive to macroscopic damage [1], and radiography and vibrational NDE as sensitive to microscopic damage. Ultrasonic NDE of composite materials are divided into two groups: flaw detection (qualitative) and property measurement (quantitative). The first group consists of flaw detection and visualization, while the second is based on the fact that as damage occurs and/or propagates.

Flaw detection

Many techniques based on ultrasonics have been widely applied and are some of the most useful approaches to nondestructive evaluation of composite damage [2]. The fundamental principle of an ultrasonic detector is that ultrasonic pulses of a frequency in the range 1 MHz to 1.5 GHz, are either transmitted through a material to a detector, or reflected back to the detector by material inhomogeneities, including internal damage. Piezoelectric transducers are commonly used for ultrasonic measurements. These transducers are usually coupled to a specimen via a liquid, most conveniently by immersing the specimen in a deionised water tank. The amplitude, frequency dependence and arrival times of detected pulses are used for flaw characterization [3-13].

a. C-scan imaging

A well-established ultrasonic technique for composite materials is the so-called ultrasonic C-scan in which an ultrasonic signal (amplitude, phase or time-of-flight delay of a signal within some time window) is plotted as an image against transducer position. The extent of damage can be examined and a depth profile of damage obtained by varying the gate for the C-scan data acquisition. Images are usually generated from specific a depth, which is defined by the position of the time window. This technique has been extensively used to detect delamination, porosity and inclusions, and to monitor the initiation and progression of damage resulting from applied mechanical loads or other environmentally degrading factors. These internal features are good reflectors of sound.

Ultrasonic C-scans are used to evaluate commercial composites during fabrication [4], to examine the damage zones in composites subjected to various impact energies and fatigue loadings [5]. An ultrasonic C-scan reveals a correlation between fatigue crack growth rates and delamination zones [6]. In one study, a full view of the progressive internal interlaminar damage, difficult to detect by common inspection methods, was successfully achieved [7]. The empirical impact behavior of the pultruded glass/polyester system was evaluated using instrumented falling weight impact testing in conjunction with ultrasonic C-Scan to detect delamination, matrix cracking, and fiber breakage [8]. When the ultrasound frequency exceeds about ten MHz, ultrasonic C-Scan is frequently called scanning acoustic microscopy (SAM) [9]. Although a typical C-scan is performed at normal incidence [10], in certain cases oblique incidence gives better contrast for transverse cracks [11] or delaminations [12]. C-scan has been used to identify induced damage and failure modes in laminated [13], woven [14] and thickness reinforced composites [15].

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[2] See Appendix E for these references

C-scan imaging is generally considered a pure qualitative method although some attempts have been made to standardize C-scan to minimize the uncertainties in attenuation measurements [16,17]. The 6 dB drop method is widely used for tile sizing of delamination defects in fiber-reinforced plastic materials [16]. However, there are certain systematic uncertainties involved in this measurement. Three main sources were found: diffraction and refraction effects, peak-frequency downshift, and nonlinear propagation in water [17]. Once a criterion for amplitude threshold is accepted, the projected damage area can be easily measured with an ultrasonic C-Scan [18,19]. A variant of C-scan techniques, known as the scanning acoustic tomography [20], represents data collected by ordinary ultrasonic C-scan apparatus as a display of in-depth information about defects in composites.

For field applications, single-sided inspection is usually achieved by a portable C-scanner with a pseudo-dry coupling system [21], or by a hand-held ultrasonic transducer with a thin layer of gel between the transducer and the specimen [22]. Air-born ultrasound was also tested for C-scan imaging [23]. Due to very big impedance mismatch, the pulse-compression technique has been applied to air-coupled testing of solid materials to improve signal to noise ratio [24]. For the same reason, there is very high direct influence of sending and receiving transducers that makes single sided inspection extremely difficult [25]. Due to difficulties in generation of high frequency sound in air, it is usually limited to frequencies within 100 KHz [26] and hence has relatively low resolution (of an order of an inch). Recently, a 250 kHz squirter-based transducer pair has been designed to favor increased loop sensitivity in through-transmission mode. Novel horn collimators are discussed that enable improved imaging of the internal structure and near-edge defects [27]. Even with the best improvements, air-born C-scan can barely detect damage in high quality composites and is not yet suitable for inspection of TxDOT FRP materials and structures.

To improve resolution, other techniques are being developed worldwide for non-contact ultrasonic inspection of composite materials based on laser generation and optical detection of ultrasound [28-32]. These methods have the potential to be very fast [28]. The technique operates without contact and at a distance of several feet or meters from the inspected part. The normalcy requirement of classical ultrasonics is eliminated, since generation occurs at the surface of the material and detection is performed directly off its surface, so parts with complex geometries can be more easily inspected [29]. Early laser based systems were based on generation of ultrasound in composite due to explosion of a thin surface layer caused by laser radiation. Recently, laser-based ultrasound systems that have sufficient sensitivity to detect typical flaws of interest in composite materials without causing surface damage to the part under test of both flat and contoured composite structures were introduced [30]. The ultrasonic sound generation and detection with a single laser has been described [31]. Two quantitative methods - the empirical constants and decibel drop - for sizing defects in fiber reinforced composites were developed [32]. Combination of two methods - laser based excitation and acoustic detection - has been tested [33]. Needless to say, that high power laser based techniques are still extremely expensive, signal to noise ratio due to inefficient thermo-elastic sound generation is not sufficient for inspection of the low quality composites used in civil engineering applications that have very high absorption of ultrasound.

As an alternative to mechanical scanning, multiple element transducers were introduced [34,35]. Besides being expensive, they usually require tight contact between the transducer array and the sample over the area of inspection. This is not easily done in case of a slightly rough surface, common for many FRP materials.

A limitation of the ultrasonic C-scan technique for the detection of damage in composite materials is the high attenuation caused by absorption in porous resin and scattering by the fibers. Due to high attenuation, the signal reflected from a defect deep inside the composite has very low amplitude compared to that scattered by fibers close to the transducer. Unfortunately, even weak scattering of coherent ultrasound radiation produces a speckle pattern similar to scattering of a laser beam by a rough surface. This speckle pattern masks and distorts the C-scan image of the defect inside the composite. A radical way to eliminate this is to use non-coherent ultrasound. This technique is called acoustography [36-38]. It utilizes an incoherent (noise like) source of ultrasound and an intensity sensitive receiver array instead of the conventional pressure sensitive array. The existing acoustography technique requires water submersion of a structure under investigation. This makes them impractical for TxDOT related inspection.

Other methods of signal recovery or C-scan image enhancement are based on digital processing of ultrasonic data [39]. With computers becoming more and more powerful, these methods gradually change from expensive and time consuming data post-processing to easily implemented real-time data development. Those methods can be roughly divided on three groups: (a) attempt to resolve structures which are closer than the distance that ultrasound travels during a time equal to the length of an ultrasonic pulse (b) signal to noise enhancement based on the idea that ultrasound scattering by the fibers and structural irregularities has different features then ultrasound reflected by defect, and (c) automatic recognition of defects according to such features as its expected shape, thus removing uncertainties related to operator experience.

Group (a). Most resolution enhancement techniques are based on comparison of the received signal with the probing pulse [40]. An exact match indicates the position of the defect. In the case of attenuative and dispersive composites, the probing pulse is highly distorted, so other deconvolution schemes are used. Typically, broadband pulse-echo A-scan signals are reconstructed in the transform domain using complex cepstrum, i.e. spectrum of the logarithm of the power spectrum of the signal. Then lower cepstrum components, which correspond to the probing pulse spectrum, are filtered out and the signal is recovered by using inverse Fourier transforms. This approach automatically measures the time delay from the front surface (i.e. it follows the front face), making it useful for inspecting slightly warped laminates, or parts with irregular surfaces [41]. It is interesting to note that from a theoretical point of view this procedure requires high signal-from-the-defect to extraneous-signal ratio, which is not the case for civil engineering composites.

Group (b). Signal to noise enhancement is based on the idea that ultrasound scattering by the fibers and structural irregularities has different features than ultrasound reflected by a defect. If a defect is big enough, it should reflect the ultrasonic pulse back if the ultrasonic wavelength is longer than the characteristic defect length. The amplitude of the wave scattered by the fibers should have a noise-like random dependence on frequency. This idea is exploited by a so-called split spectrum technique [42] in which the received signal is filtered through a bank of narrow band filters and the phase of the output is compared. Unfortunately, this method is not applicable to TxDOT related FRPs because they usually have structural irregularities of the scale of expected defects, which cannot be filtered out.

Another approach is based on idea that certain frequencies can contribute more to the noise then others. If by proper filtration those frequencies are suppressed, signal from the defect can have higher amplitude relative to noise amplitude [43]. The noise spectrum can be estimated by collecting data from non-defective region of a composite. The signal to noise ratio can be improved either by making the noise spectrum as flat as possible (white noise) [44], or by adapting the spectrum to the expected signal from the defect [45]. The neural network technique is frequently used to construct an optimal filter [46,47]. If a comparison of ultrasonic echograms with the theoretical models is performed [47], automatic defect recognition can be achieved at no additional computational cost. Typically, adaptive filtration can improve signal to noise ratio on a factor of 5 to10 dB and could be recommended as an additional improvement of ultrasonic inspection methods for TxDOT related composites.

A novel approach to the problem of adaptive filtration uses a wavelet-based method. By combining the time domain and the classical Fourier analysis, the wavelet transform simultaneously provides both spectral representation and temporal order of the signal decomposition components. To construct a C-scan image from the wavelet transforms of the A-scan signals, a selection process of the wavelet coefficients, followed by an interpretation procedure based on a windowing process in the time-frequency domain is implemented. For example, when reflection from the opposite side must be monitored to measure ultrasonic attenuation, all wavelets with arrival times shorter than the opposite side echo are windowed out [48]. This can be extremely useful for inspecting low quality composites of double through-transmission, or for finding no-glue areas of adhesively bonded composite structures.

Group (c). Even though automated C-scan that incorporates such advanced features as digitization and storage of analog data in real-time has become possible, C-scan images are still evaluated by visual inspection. Several techniques have been proposed as viable supplements to this human inspection. A simple fractal algorithm has been implemented for such an exercise [49] to automatically recognize defects in a C-scan image. Another approach, based on classifying ultrasonic resonance spectra using a neural network and thus reconstructing the in-depth structure of composite, has been undertaken [50]. Although their implementation may be useful in the future, automatic features recognition requires significant research and development, which is unlikely to be completed within the near future.

b. B-scan imaging

Another type of ultrasonic imaging is based on representation of an entire signal (usually in gray scale) against the ultrasonic probe position when the probe is scanning along a single line (B-scan). The resulting image represents a cross –section of the composite. Since the B-scan displays both time domain and spatial domain information, signal processing of digitized ultrasonic B-scan data can be applied to quantify damage in composites. The B-scans were analyzed with respect to velocity, damping and statistical properties [51]. In general, the “6 dB drop" method can be applied to size a delamination in FRP. However, the accuracy of this method depends on the size and shape of the delamination relative to the ultrasound beam [52]. The accuracy also depends on use of empirical constants to relate the reduction in signal amplitude from a defect that is smaller than the probe diameter to the signal from a defect that is equal to or larger than the probe diameter [53].

An alternative method for sizing small defects is by measuring the amplitude of the signal reflected by the defect itself [54]. Since a B-scan does not require area scanning, it can be performed with the use of a portable or hand-held device similar to the on-line system based on the Boeing-designed Mobile Automated Scanner (MAUS) III, a portable ultrasonic inspection instrument intended for in-service inspection of aircraft. Such a device has been attached to a pultrusion line and provided continuous real-time C-scan data for the fabricated aircraft stiffener [55]. Since basic physics information of C-scan and B-scan images are the same, all data development methods available for the C-scan technique are equally applicable for B-scans. Because variations of mechanical properties of low quality composites are expected to be high for flaw detection, they can be compared only with themselves. Hence, certain kinds of point-to-point inspection are necessary to perform flaw detection and defect size measurements. Most plausibly, it should be B-scan imaging.

Mechanical Property Measurement

c. Quantitative NDE

Propagation of ultrasound in composites is governed by the elastic properties of the composite, which makes ultrasonic technique well suited for measurement of mechanical properties. In order to measure mechanical properties the problem of elastic wave propagation in a composite material needs to be solved. As a rule, the solution is easier to obtain in the frequency domain. Due to the presence of tensile free boundaries in most composite components, certain type of elastic resonances can be excited in them. Accordingly, spectral analysis of an ultrasonic signal is frequently used for quantitative NDE of composites. Resonant frequencies have been used for the study of tensile and the shear elastic moduli of fiber reinforced composites [56], for ultrasonic measurements related to the evolution of the structure in a curing epoxy resins [57], for measurements of hydrolytic damage detection in glass FRP [58], and for detection of flaws in structural members [59]. Usually, through-thickness resonances are used due to much easier interpretation of experimental data [60]. However, structural resonances of composite elements, which can be performed at much lower frequency, were also implemented for different structural element geometries [61,62].

For laminated composites with a regular layer sequence, "internal" resonances, due to periodicity of composite properties (so-called Floquet waves) can be used for NDE purposes [63]. A comparative study on different ways to determine the mechanical properties of glass fiber composite materials highlights the accuracy of the results obtained by means of measurement of ultrasonic wave velocities, compared to a static characterization method by tensile testing [64]. The elastic moduli of composites are integral characteristics that reflect almost any degradation of the composite, including imperfect fiber-matrix interphase [65], porosity [66], moisture absorption [67], fatigue [68] and thermal degradation [69], as well as changes in resin content [70], or even different cure conditions [71]. Although these changes can easily be measured ultrasonically, they are frequently within variations of elastic moduli from one composite to another, or even for different areas within the same composite structural elements. Hence, ultrasonic velocity measurements cannot be used for quality control of composite materials, but can be utilized for monitoring the degradation of highway structures made of composites.

Slightly more complicated analysis of ultrasound propagation in composite allows measurement of complex elastic moduli, and attenuation in composites [72]. An ultrasonic attenuation measurement has been used for non-destructive assessment of porosity in composite repairs [73]. It has been shown that ultrasonic attenuation measurements obtained from the amplitude of the echo returning from the backwall of the structure provide a satisfactory technique for use in the field, where immersion testing is not possible. Tests have been carried out on both good and poor quality repairs and it has been shown that satisfactory measurements can be obtained using commercially available equipment that is suited for field use.

It was observed that ultrasonic attenuation is sensitive to thermal fatigue, increasing with increasing number of thermal cycles primary due to fiber-matrix debonding [74]. Good correlation of the ultrasonic attenuation with the shear and flexural strength of composite laminates has been obtained [75]. Fatigue loading the glass FRP to high stresses (above 50% of the static failure stress) induced extensive damage that consisted of debonding of the surface glass fiber tows together with a complex array of cracks and delaminations within the composite, this damage being easily detected [76]. Unfortunately, low quality composites show high and non-uniform scattering of ultrasound on local inhomogeneities, which cannot be distinguished from attenuation due to absorption of ultrasonic waves or wave scattering by fatigue micro-cracks are pores.

Attenuation measurements are subject to all of the problems typical for velocity measurements, but are much more difficult to perform. However, since changes in attenuation are usually much bigger then those in ultrasonic velocity, it is possible to use attenuation measurements as a part of manufacturing quality control. The technique may be appropriate for inspection of FRP structural elements intended for highway related applications.

Recent theoretical and experimental studies have demonstrated that weakly or incompletely bonded interfaces exhibit highly nonlinear behavior [77]. One of the acoustic manifestations of such nonlinearity is the modulation of a probing high-frequency ultrasonic wave by low-frequency vibration [78]. The vibration varies over the contact area, modulating the phase and amplitude of the higher frequency probing wave passing through the interface. In the frequency domain, the result of this modulation manifests itself as side-band spectral components with respect to the frequency of the probing wave. The excess nonlinearity is produced also by the strong local nonlinearity of microcracks whose opening is smaller than the particle displacement. Parametric modulation via crack-closure significantly increases the stress-dependence of fatigued materials. Experimental results are presented to illustrate that the nonlinear acoustic parameters are earlier and more sensitive indicators of fatigue damage than their linear counterparts [79]. Although promising, measurement of nonlinear properties is a new and not well established technique. Although fatigue cycles significantly increased the second harmonic, even when no damage is yet observed by C-scan [80], intact composites are also much more nonlinear than the metals. Low quality composites usually have relatively high porosity and a sufficient number of micro-voids that they may possess nonlinear behavior. More experimental data is required to make this technique practical for inspection of FRP highway structures.

d. Guided and surface waves

A simple shaped object can support guided (Lamb) waves that can travel along the structure instead of propagating into the depth of it. In many cases it allows inspection of a large area at once, thus avoiding mechanical scanning [81]. An image, similar to a B-scan can be generated from a point probe that can use a dry contact transducer [82], laser based generation and detection [83], or a combination of both [84]. Since generation of Lamb waves utilizes rather long ultrasonic pulses, air-coupled transducers can be more easily used [85].

There are an infinite number of guided wave modes. With a few exceptions, each mode is characterized by its cut-off frequency. The cut-off frequency is that frequency below which a given mode cannot propagate. Each mode can be treated as a mixture of longitudinal and shear waves. Shear waves are usually better reflected from imperfect interfaces - one side of the interface can slide against another side. Hence, Lamb waves can be more sensitive to internal defects [86] and imperfect bonds [87]. The detection techniques are based on reflection of Lamb waves from a defect [81], change of amplitude [88] or mode shape [84] near a defect, and their attenuation [89]. Wavelet transform are routinely used to separate the ultrasonic Lamb wave modes [90,91]. The most attractive feature of guided waves is that their sensitivity to a discontinuity is defined by the ratio of defect size to the thickness of the structural element, regardless of wavelength. Thus, low frequency ultrasound, which is less sensitive to scattering from fibers, can be used for inspection. However, only relatively simple shaped elements such as plates, bars or cylinders can be inspected with this technique.

Chapter 3 – Test Samples

3.1 INTRODUCTION

This Chapter reports the results achieved on Task 2. The Project Agreement summarizes the task as follows.

Task 2. Design, fabricate, and procure test samples.

Samples for the acoustic emission and ultrasonic research programs have been designed and fabricated. These samples will also be used for research on other nondestructive inspection methods such as visual, dye penetrant, and thermovision. The items under this task that refer to scaled models have not been completed pending a final decision about the approach to be used for FRP structural members. The approach outlined in the Project Agreement, which is based on RTP-1, has turned out to be impractical for the numerous fabrication methods and structural configurations that are likely to be used for FRP structural members.

3.2 SAMPLES FOR ACOUSTIC EMISSION RESEARCH

A range of specimens became available from TxDOT project 0-1773 "Applications for Composite Materials in TxDOT". Many of these were full-scale specimens and included the following:

a. Glass fiber reinforced isopthalic polyester pultruded beam with a concrete deck. The beam was fabricated by Strongwell Corporation and is shown in figure 3.1 without the concrete deck.
   Dimensions: Wide flange shape, 30 foot long, 12 inch flange width, 12 inch deep, and 0.5 inch thick.
   Deck: Reinforced concrete 48in x 6in x 30ft
   Fabrication method: Pultrusion
   Material specification
      Fiber: 366 Type 30® E Glass fiber (Owens Corning) unidirectional along the length of the beam
      Resin: AROPOL 2036C Isopthalic polyester (Ashland Chemical)

b. Glass fiber reinforced vinyl ester pultruded beam with a concrete deck. The beam was fabricated by Bedford Reinforced Plastics Inc., and is shown in figure 3.2.
   Dimensions: Wide flange shape 30 foot long, 12 inch flange width, 12inches deep, and 0.5 inch thick.
   Deck: Reinforced concrete 48in x 6in x 30ft
   Fabrication method: Pultrusion
   Material specification
      Fiber: 366 Type 30® E Glass fiber (Owens Corning) unidirectional along the length of the beam
      Resin: CORVE 8182 vinyl ester (Interplastic Corporation).

Figure 3.1 - Glass Fiber Reinforced Isopthalic Polyester Pultruded Beam with Shear Connectors, Prior to Casting Reinforced Concrete Slab

Figure 3.2 - Glass Fiber Reinforced Vinyl Ester Pultruded beam with Concrete Deck

c. Carbon and glass fiber reinforced vinyl ester pultruded beam with a concrete deck. The beam was fabricated by Strongwell Corporation and is shown with the concrete deck in figure 3.3.
   Dimensions: Wide flange shape with double webs 30 foot long, 6 inch flange width, and 8 inches deep.
   Deck: Reinforced concrete 36in x 6in x 30ft
   Fabrication method: Pultrusion
   Material specification
   Fiber: Hybrid HERCULES AS 4 (36K) Carbon fiber and E glass fiber.
   Resin: DOW chemical Derakane 411-350 vinyl ester with 10% of styrene.

d. Filament wound oil field pipe was assembled as arches with a concrete deck. The pipes were fabricated by Fiber Glass Systems Inc., and are shown in figure 3.4.
   Dimensions: Pipes of various diameters were used to form the 30 foot long arches. The following pipes were used: 4.25 inch diameter line pipe for the vertical members, 6.5 inch diameter line pipe for the inclined members, and 5 inch diameter downhole pipe for the horizontal members.
   Deck: Reinforced concrete 54in x 6in x 30ft
   Material Specification
   Fiber: E glass fiber
   Resin: Aliphatic amine cured epoxy

e. Glass reinforced trapezoidal hand lay-up vinyl ester beam with a concrete deck. The beam was fabricated by Tankinetics Inc., and is shown in figures 3.5 and 3.6.
   Dimensions: Trapezoidal box 30 foot long, 18 inches wide at midspan. The width was gradually reduced towards the ends starting 10 feet from both ends. The tension flange is 3 inch thick. Both webs are 0.5 inch thick.
   Deck: Reinforced concrete 48in x 6in x 30ft
   Material Specification
   Fiber: E glass fiber
   Resin: Derakane 411-350 vinyl ester

f. The FRP beams listed as items “a” through “d” and the FRP pipes used to fabricate item “e” were available without the concrete deck. These items were procured new at the beginning of the project.

g. Selected items “a” through “f” were damaged with deliberately applied impact loads, and during testing. These specimens were tested to provide an AE database from damaged specimens.

Figure 3.3 - Carbon Fiber and Glass Reinforced Vinyl Ester Pultruded Beam with Concrete Deck

Figure 3.4 - Filament Wound Pipe Assembled as Arches with Concrete Deck

Figure 3.5 - Trapezoidal Hand Lay-up Beam with Concrete Deck

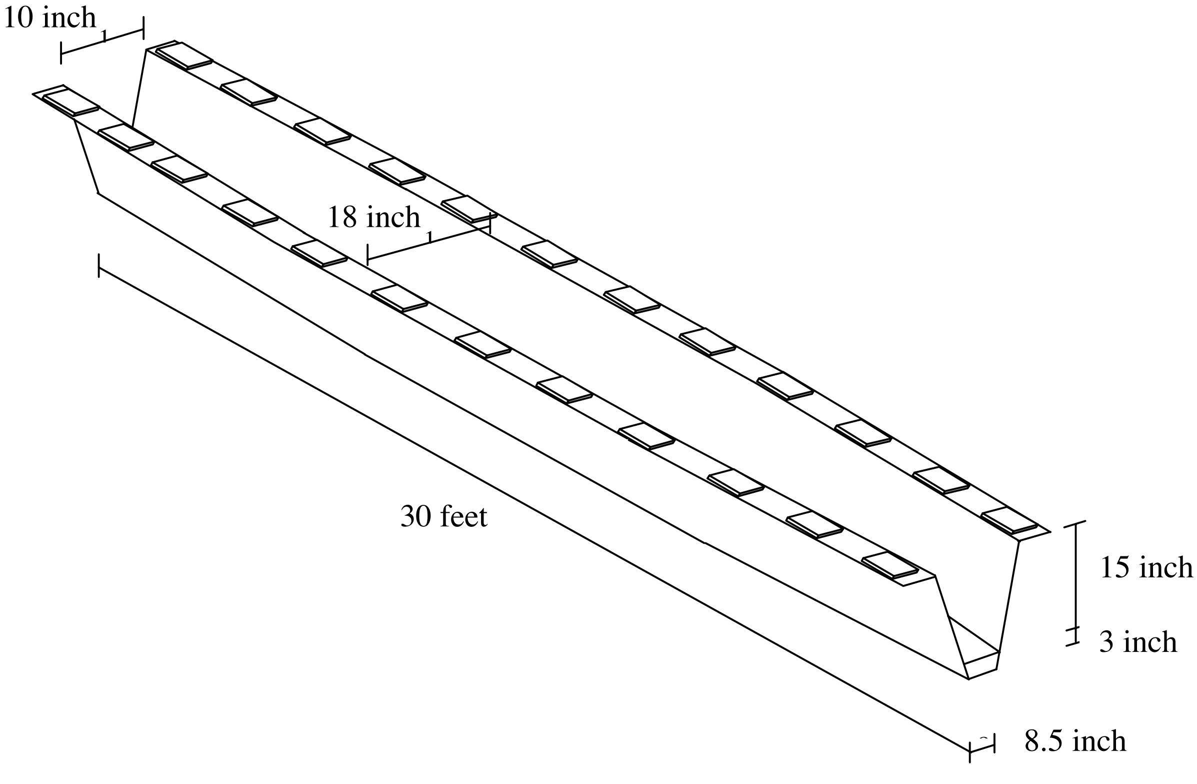


Figure 3.6 – Dimensions of Trapezoidal Hand-lay Up Beam

Two FRP vessels and a pipe were obtained for this project. Details of these test objects follow.

h. RTP-1 demonstration vessel shown in figure 3.7. The vessel walls were filament wound with contact molded heads.
Dimensions: 48 inch diameter, 72 inches high with 26 inch diameter access manway
Capacity: 457 gallons.
Material specification
  Fiber: E glass fiber
  Resin: HETRON 197 vinyl ester
Condition: New vessel made as a fabricator qualification vessel under the provisions of ASME RTP-1.

i. Contact molded (hand lay-up) FRP vessel shown in figure 3.8
Dimensions: 38-inch diameter with 3 nozzles on the top and 5 nozzles on the side.
Material Specification
  Fiber: E glass fiber
  Resin: vinyl ester
Condition: Vessel had been in use, but was removed from service because of damage.

j. Fiber glass filament wound pressure pipe overlaid with carbon fiber layer
Nominal dimensions: 8 inch diameter, glass fiber layer 0.325 inch thick, carbon fiber layer 0.025 inch thick.
Material Specification
  Fiber: E glass and aerospace carbon fiber similar to AS-4D fibers
  Resin: HETRON 922 vinyl ester

Some undamaged areas of items a through f were cut to make small and intermediate samples. Theses small samples include:

k. Dog bone tensile test samples. 23 inch x 6 inch samples were cut from the glass/polyester, glass/vinyl ester, and carbon/vinyl ester composite beams. A representative sample is shown in figure 3.9. As indicated in the figure, the sample will be tested in tension.

l. Buckling test samples. 6 inch long specimens were cut from the carbon/vinyl ester composite beam. The samples will be tested in compression, which will cause buckling/delamination failure at the webs. The sample instrumented for testing is shown in figure 3.10.

m. Short beam shear samples. 1 inch x 0.5 inches x 6 inch samples were cut from the glass/polyester, glass/vinyl ester, and carbon/vinyl ester composite beams. The samples will be tested in bending as shown in Figure 3.11. The geometry of the sample and the test set up causes high shear stress near the support areas.

n. Flexural test samples. 1inch x 0.5 inches x 6 inch samples were cut from the glass/polyester, glass/vinyl ester, and carbon/vinyl ester composite beams. The samples will be tested in bending as shown in Fig.3.12.

o. Peeling failure samples. Dow Chemical Company is preparing samples, which are designed to reproduce secondary bond failure under test loads. The design for these samples is modified from ASTM F 521 (figure 2) and is as shown in Fig. 3.13.

p. Samples from the glass/polyester and glass/vinyl ester beams were machined to ensure a tension failure. Portions of the tension flange and the web were removed. To avoid buckling, the compression flange was braced. The length of the specimen was 8 feet - 2 inches. Figure 3.14 shows a representative test specimen.

Figure 3.7 - RTP-1 Demonstration Vessel

Figure 3.8 – Contact Molded FRP Vessel with In-service Damage

q. A high performance aerospace carbon fiber reinforced composite has become available through a related research project for the U. S. Navy. AE data from this material will help bracket the expected range of infrastructure composites. The composite panel, which has been subdivided into smaller specimens, is shown in figure 3.15.

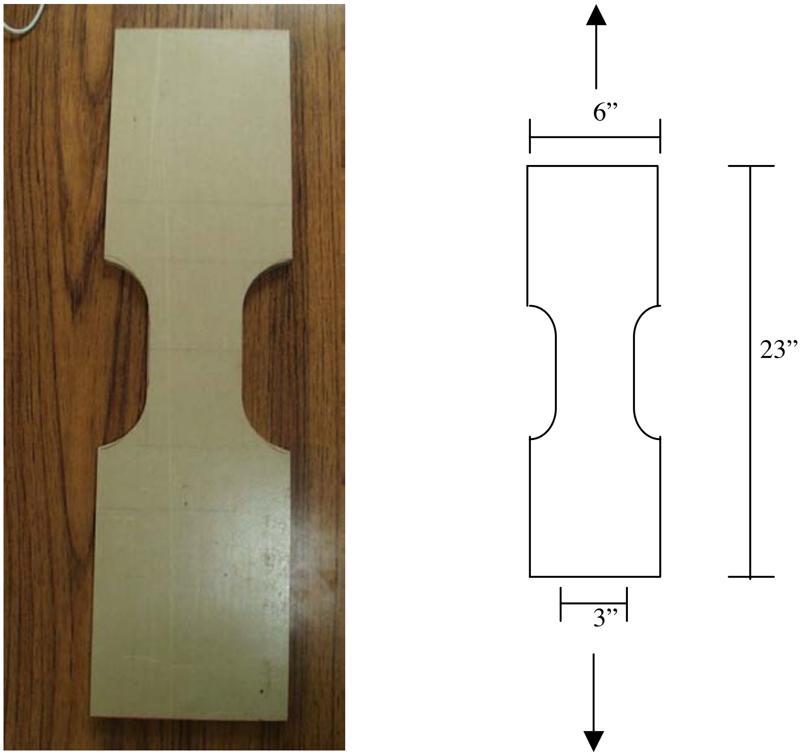


Figure 3.9 - Tensile Test Specimen Cut From Glass Fiber Reinforced Vinyl Ester Beam

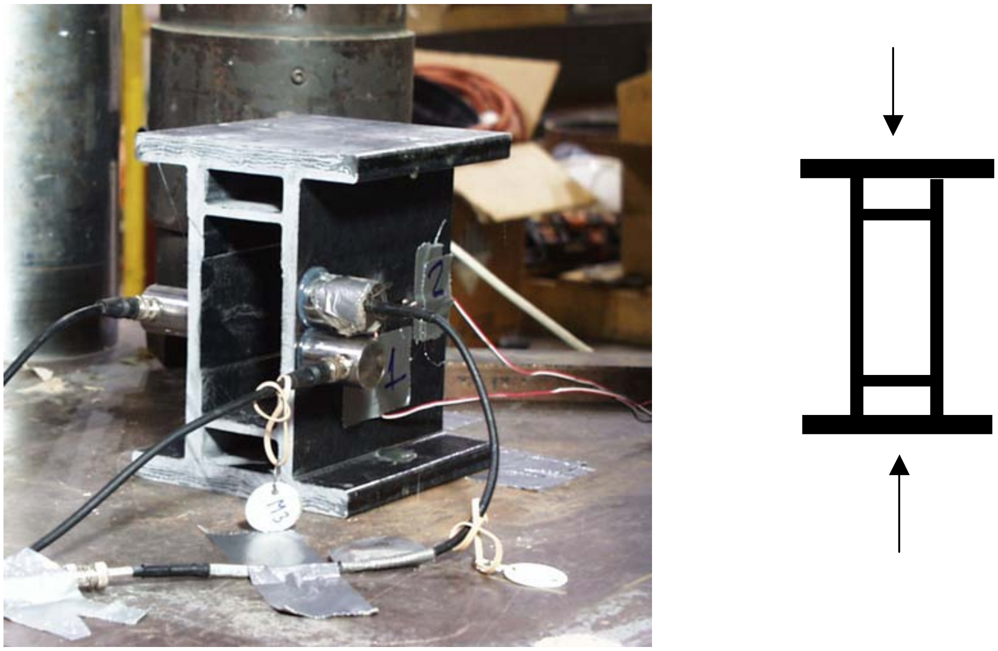


Figure 3.10 – Carbon/glass Fiber Reinforced Vinyl Ester Buckling Specimen Instrumented Ready for Test

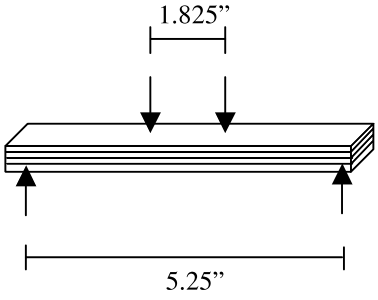


Figure 3.11 – Details of Short Beam Shear Beam Sample

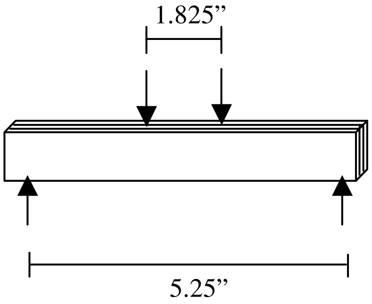


Figure 3.12 - Details of Flexural Sample

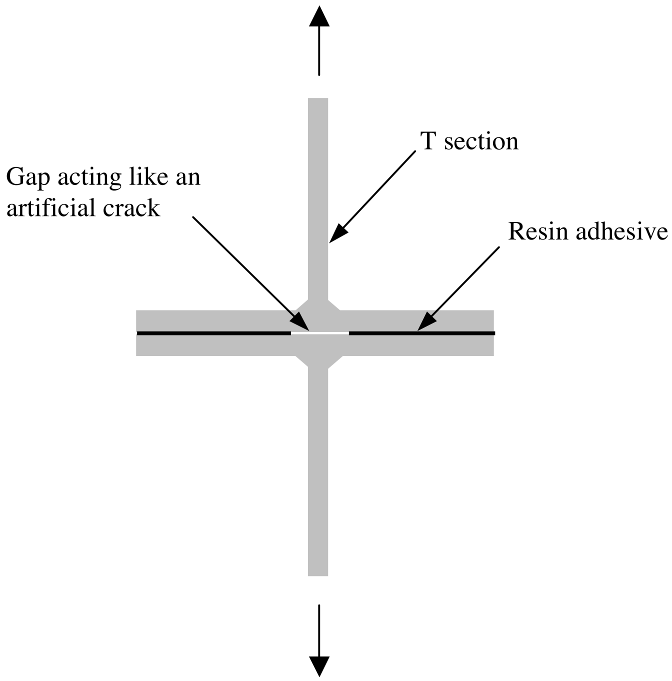


Figure 3.13 – Details of the Peel Test

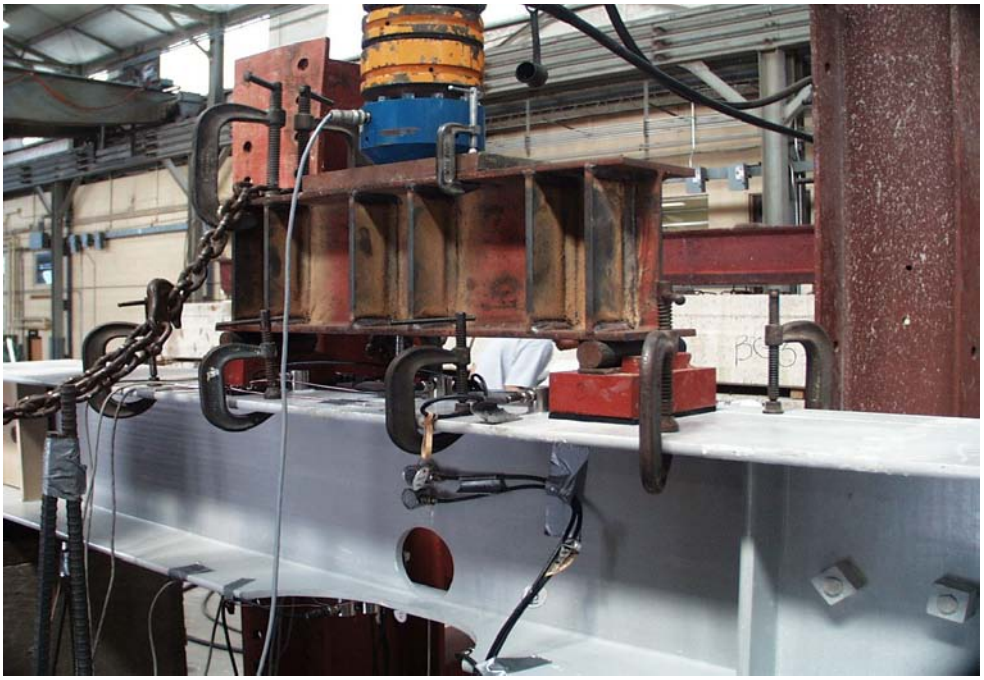


Figure 3.14 – Specimen Machined to Ensure a Tension Failure

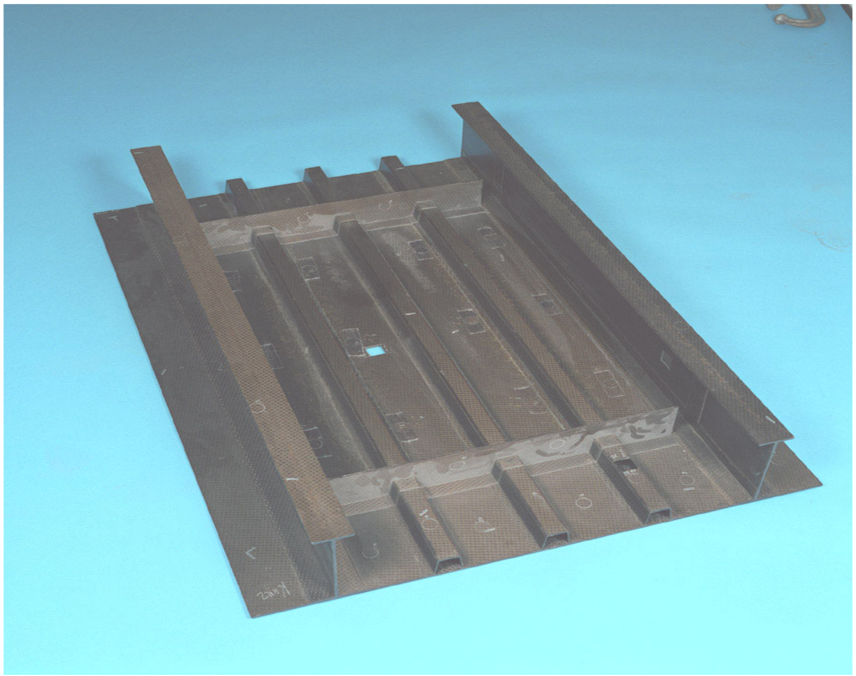


Figure 3.15 – Aerospace Composite Panel

3.3 SAMPLES FOR ULTRASONICS RESEARCH

Three types of samples were prepared.

a) Samples of industrially manufactured composites for adjustment of ultrasonic equipment to typical composites as media for elastic wave propagation.

b) Sample with artificial defects to calibrate ultrasonic equipment for flaw detection.

c) Samples of secondary joints.

Samples of type “a)” were cut from composite structural elements acquired for mechanical testing by the University of Texas (UT) Ferguson laboratory before and after the test. It include pultruded, contact molded, and filament wound beams. A number have been damaged during structural testing and will provide excellent test objects. The following samples were obtained.

- Glass fiber reinforced isopthalic polyester pultruded beam listed as sample “a” in section 3.2
- Carbon and glass fiber reinforced vinyl ester pultruded beam listed as sample “c” in section 3.2.
- Glass reinforced trapezoidal hand lay-up vinyl ester beam listed as sample “e” in section 3.2
- Glass reinforced epoxy pipe listed as sample d. in section 3.2, glass reinforced vinyl ester pipe with a carbon fiber overlay listed as sample “j” in section 3.2, and carbon fiber reinforced vinyl ester pipe.

Specimens were cut approximately 3 feet long. No further preparation was made before ultrasonic inspection. After inspection samples were sliced using a diamond saw and polished for visual inspection of composite quality (different types of manufactured defects)

Two samples of type “b)” containing two different kinds of artificial defects were manufactured at the UT IMPACT Laboratory. Defects were made to simulate delaminations between fiber mats in glass/epoxy composites. In one sample 1 mil thick Teflon inserts were put between fiber mats at different depth, in another inserts were made of two layers of polyethylene without an adhesive layer between them. Size and position of inserts in shown in Figure 3.16

Type “c)” samples with secondary joints were cut from industrially manufactured glass fiber reinforced isopthalic polyester pultruded beam. Secondary bond was with Magnabond 56-3 epoxy resin and modified polyamide curing agent. The product is manufactured by Magnolia Plastics. FRP dowels spaced along the joint supplemented the bond.

Samples used for TxDOT Project 0-1774 "Effect of Wrapping Chloride Contaminated Structural Concrete with Multiple Layers of Glass Fibers/Composites and Resin" are also used as test specimens. They include about 1/8" thick layer of glass/epoxy composite wrapped around concrete columns and cemented by different adhesives. A complete list of specimens is listed in TxDOT Project 0-1774

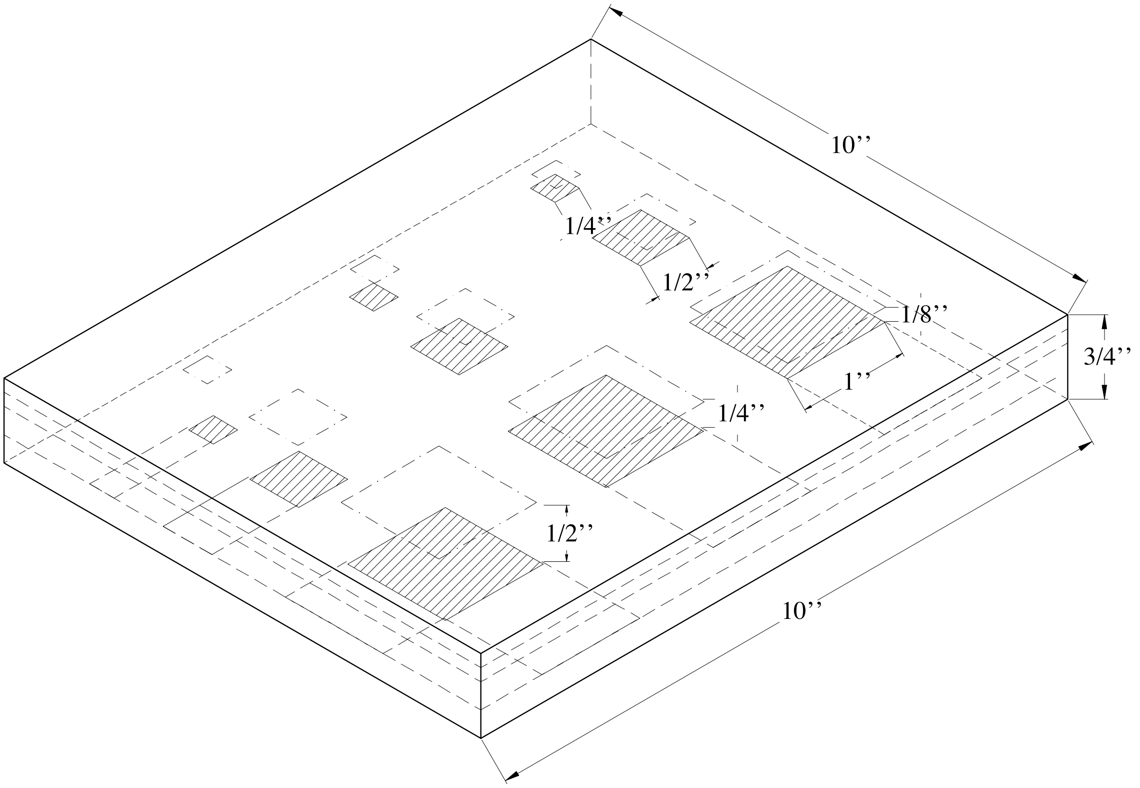


Figure 3.16 - Sketch of position of artificial defects in glass fiber reinforced epoxy composite test sample.

Several samples were manufactured in Texas A&M University from the glass fiber reinforced isopthalic polyester pultruded beam samples. Epoxy resin (Epon 828) with Epon 3140 curing agent was used to form an adhesive layer between 1/2" thick composite plates. Calibrated spacers placed between the composite plates 4 inches apart, controlled layer thickness. Adhesive layers of "zero" thickness (tight contact under 10 lb/in^2 pressure), 2 mil, 10 mil, and 50 mil were manufactured at room temperature.

Chapter 4 – Experimental Equipment

4.1 INTRODUCTION

This Chapter reports the results achieved on Task 3. The Project Agreement summarizes the task as follows.

Task 3. Assemble experimental equipment and conduct preliminary tests.

Equipment for acoustic emission monitoring and ultrasonic examination is summarized in this chapter. Conventional structural test equipment such as loading frames, strain gages, etc., is not described. Emphasis is on ultrasonics with the effort directed towards suitable modification of conventional UT techniques so that they can be applied to composite bridges, and highway and other transportation related structures.

4.2 ACOUSTIC EMISSION DATA ACQUISITION INSTRUMENTS

AE Data Acquisition. Three AE data acquisition instruments are being used for this research. Physical Acoustic Corporation (PAC), Princeton, New Jersey, manufactures all three. Details are given below.

- 24 channel Transportation Instrument. The instrument is shown in figure 4.1. The Transportation Instrument is the most basic general purpose AE data acquisition system. It is easy to use and easy to set up. The 24 channels provide very good coverage for full-scale specimens. Data from this instrument can be analyzed with the widely used VTRNSMON software that runs on PC style computers.

- 6 channel LOCAN 320, also referred to as a 320 Location Analyzer. The LOCAN is the advanced research instrument which allows the users to set hardware parameters according to the specimen geometry, type of materials, and AE sensors. In addition, 2 channels can be set as guard sensors, which can be used to eliminate unwanted noise originating from outside the region of interest. Data acquired from the LOCAN can be analyzed with the MISTRAS analysis software (see following bullet). Figure 4.2 shows the LOCAN instrument being used to monitor background traffic noise on a concrete bridge.

- 6 channel MISTRAS system. The MISTRAS is currently a “state of the art” AE instrument which not only has all of the LOCAN’s functions, but it also can acquire digital waveforms, which are a useful tool for signature analysis and defect classification. The MISTRAS includes an extensive suite of software programs that can be run on any Windows based computer. The MISTRAS system is shown in figure 4.3.

AE Sensors. Four types of AE sensors are available for use on this project. The first are R15I resonant sensors, which are resonant at 150 kHz. These sensors have been widely used on composite tanks, vessels, and manlifts. Over 20 R15I sensors are available, which is a sufficient number to cover a full-scale specimen. The second and third are resonant sensors centered at 60 and 300 kHz. The low frequency sensors are used for highly attenuating materials such as FRP with a high resin content. The high frequency sensors are used when high levels of extraneous noise, such as traffic noise are present. The fourth type are wideband sensors. These sensors are not resonant at a specific frequency. Instead, they are able to capture data over a broad range of frequencies. Wideband sensors are less sensitive than resonant sensors but provide valuable source location and defect signature information.

Test Setup. Ancillary supporting equipment such as the loading frame for the full-scale tests, rams, load cells, hydraulic systems, and spreading beams have been assembled or fabricated. Strain gages and linear pots have been procured, and the small-scale test setup for the 4-point bending test has also been fabricated.

Figure 4.1 - Transportation Instrument.

Figure 4.2 – LOCAN 320 Instrument Being Used to Monitor Traffic Noise

Figure 4.3 – MISTRAS System

4.3 ULTRASONIC EQUIPMENT

The wave propagation laboratory of Texas A&M University is well equipped with top of the line ultrasonic NDT devices. It has three water immersion ultrasonic scanners manufactured by "Testech", "Apace", and "Sonix". The latest and most advanced scanner made by "Sonix" is shown in figure 4.4.

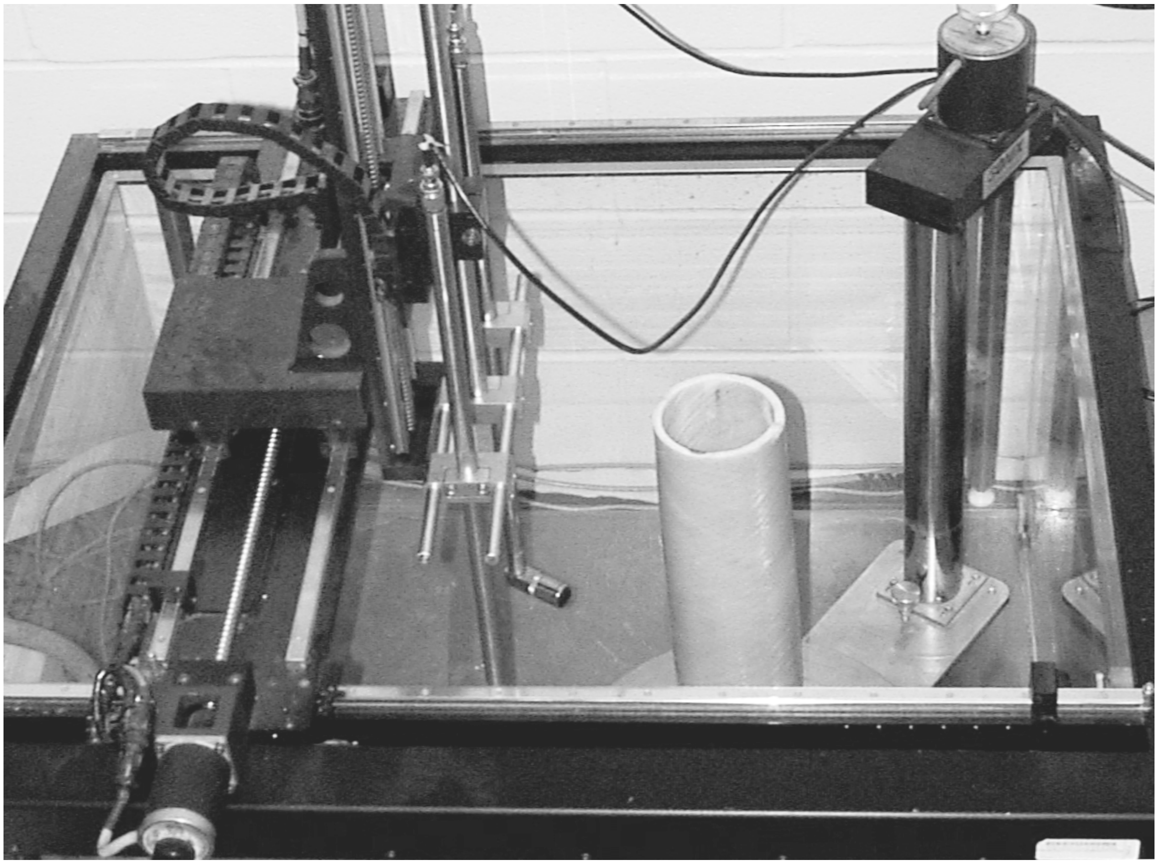
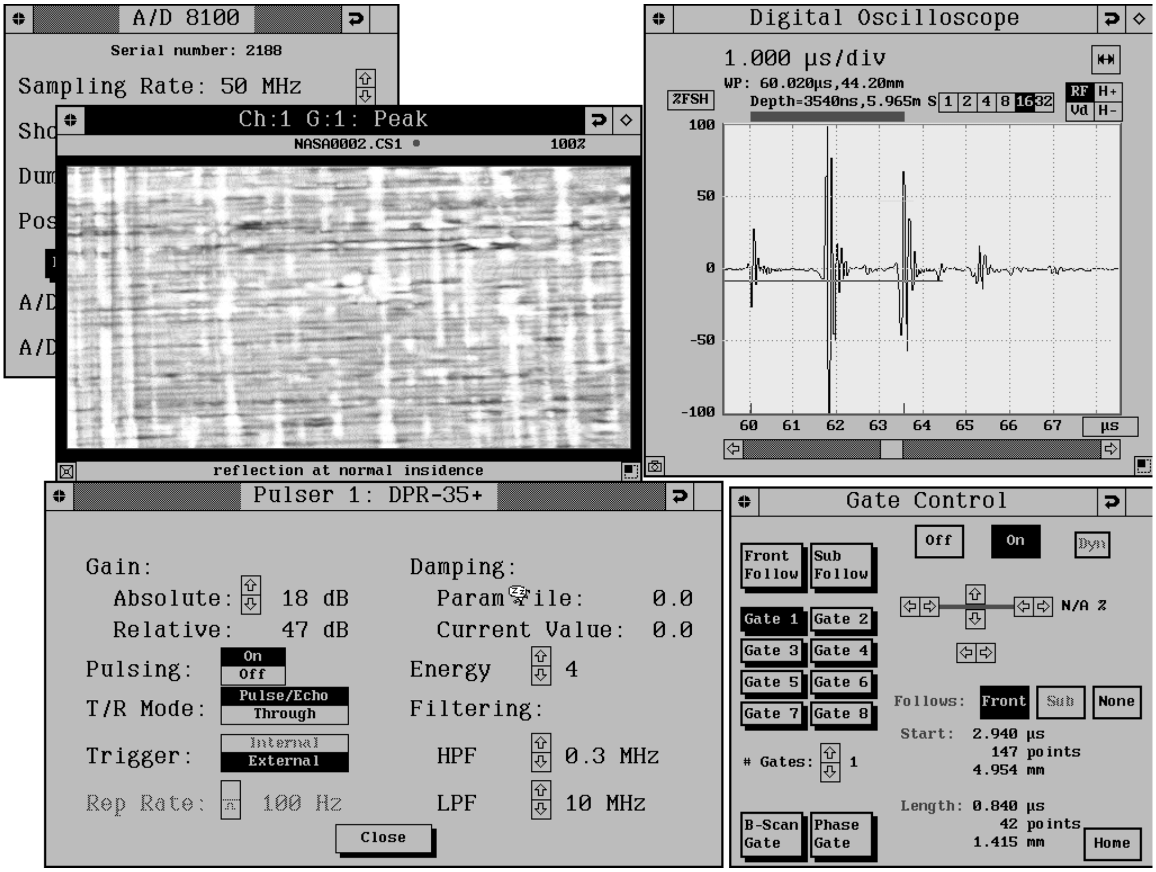


Figure 4.4 - Ultrasonic Scanner and Water Immersion Tank.

The scanner allows for dimensional (X, Y, Z and rotation) scanning along curved sample surface. A set of attachments allows use of a single transducer in the pulse-echo mode, and several transducers either in through-transmission or in the pitch-catch position. Scanner is step motors driven and has mechanical resolution of about 0.04 mil. Data acquisition system is build around WaveEdge STR*8100 A/D board which is a high-speed waveform digitizer with a 100 MHz transient sampling rate. The STR*8100, offering 8-bit resolution, and fast data transfer directly into the PC memory space.



A/D 8100

Serial number: 2188

Sampling Rate: 50 MHz

Ch:1 G:1: Peak

NASA0002.CS1 100%

reflection at normal insidence

Digital Oscilloscope

1.000 µs/div

WP: 60.020µs,44.20mm

Depth=3540ns,5.965m

Pulser 1: DPR-35+

Gain:

Absolute: 18 dB

Relative: 47 dB

Pulsing: On / Off

T/R Mode: Pulse/Echo / Through

Trigger: Internal / External

Rep Rate: 100 Hz

Damping:

Param File: 0.0

Current Value: 0.0

Energy 4

Filtering:

HPF 0.3 MHz

LPF 10 MHz

Gate Control

Gates: 1

Follows: Front

Start: 2.940 µs

147 points

4.954 mm

Length: 0.840 µs

42 points

1.415 mm

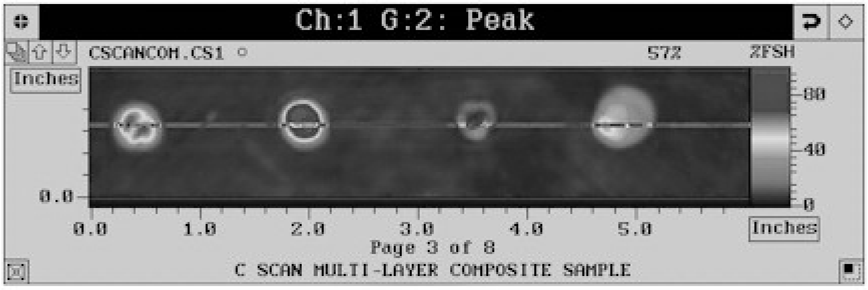
N/A %

Figure 4.5 - A Screen-shot of Computer Display of "Sonix" Ultrasonic Scanner.

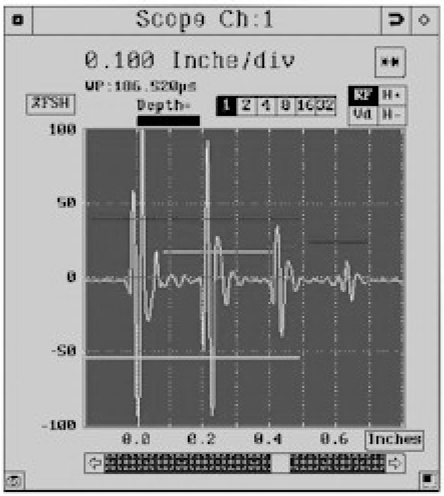
Extensive software has been written for ultrasonic data collection and image processing. A screen-shot of computer display when scanner is operating in figure 4.5. C-scan of graphite/epoxy composite in reflection shows lack of epoxy along several strips of graphite fibers. Time position of window gate for C-scan is displayed in digital oscilloscope window. Several control windows are opened and can be used to adjust scanning and data acquisition parameters. The device is capable of collecting the signal (see figure 4.6.b), performing C-scan data collection with up to 8 time gates (figure 4.6,a), performing multiple B-scans (figure 4.6.c), performing signal analysis in the frequency domain (Fourier transform), and making a simple image analysis.

A large variety of ultrasonic transducers have been tested for ultrasonic inspection of highway related composites. It should be noted that high frequency sharp focused transducers typically used for inspection of high quality composites used in aircraft industry are not applicable to inspection of low cost composites. List of tested transducers (made by Panametrics) is presented in Table 3. No single transducer can cover all possible defects in composites. Based on preliminary tests performed for quality control of composite material and adhesive joints we have chosen 5 MHz focused transducer for near surface defects and 1 MHz 0.5” diameter flat transducer for inspection of thick composites.

C-Scan



A-Scan



B-Scan

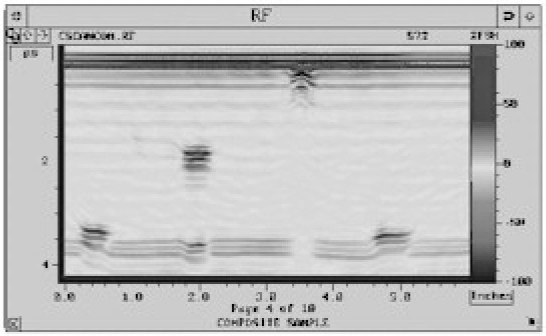


Figure 4.6 - Different Types of Ultrasonic NDE Data Representation.

Table 3 - List of ultrasonic transducers (Panametrics)

Frequency MHz	Nominal Element Size	Transducer Part Number
0.5	1.125" (29mm	V391-SU
1.0	1.00" (25mm) 0.50" (13mm)	V302-SU V303-SU
2.25	1.00" (25mm) Focused 0.50" (13mm)	V304-SU V306-SU
5.0	1.00" (25mm) Focused	V307-SU

Laboratory assembled ultrasonic equipment. Immersion scanners are not applicable for field inspection, although they are well suited for development of the technique. Hence, several types of hand scanners are designed and will be tested. Principal diagram of one of them, which uses sonic technique for scanner position monitoring and water filled buffer column with semi-permeable front membrane, is shown in figure 4.7. To simplify development of software drivers for the scanner it utilizes the same WaveEdge STR*8100 A/D board as Sonix scanner.

To keep device portable we use PCPR-100 (PC1000) plug-in single board pulser/receiver made by Santa Barbara NDT Company. The PCPR-100 is a unique ultrasonic pulser/receiver featuring square wave and tone burst pulser capabilities, as well as broadband and tuned mode receiver operation, in one completely digitally controlled package. This board-mounted system fits into a full-size or portable host computer ISA slot and communicates with directly with the software system. Through software, the user has full control of all board functions, and can save the board set-ups for future use.

Board input-output parameters, which define its capability to excite and receive ultrasonic pulses, are listed below:
Pulser Voltage 25 to 375 V
Damping 40 to 640 ohms
Pulse Shape +Bi-polar, -Bi-polar, +Unipolar, -Unipolar
Number of Cycles 1 to 8
Pulse Duration (Frequency) 50 (20.48 MHz) to 1,520 nsec (640 Hz)
Rise Time < 7 nsec
Gain 0 to 100 dB in 1 dB step
Low-pass Filter Cutoff Frequencies 50, 24, 14, 9, 3, 2.6, 2.4, and 2.2 MHz
High-Pass Filter Cutoff Frequencies 0.1, 0.5, 2.3, and 2.8 MHz

A photograph of a portable scanner with an ultrasonic probe, which uses plastic buffer rode for low frequency inspection of thick composites, is shown in figure 4.8. Computer monitor displays ultrasonic pulse reflected from artificial defect inside plate and several lines of pulser/receiver and ADC board's parameters, which can be adjusted prior to Scanning.

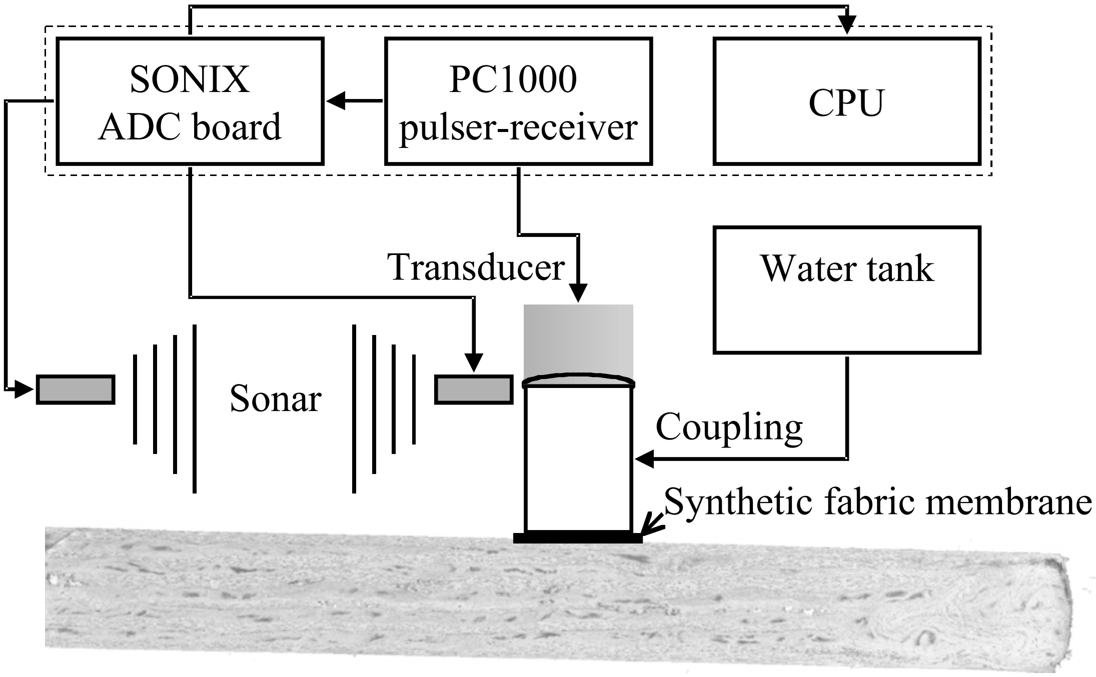


Figure 4.7 - Principal Diagram of Portable Ultrasonic Hand-held Scanner.

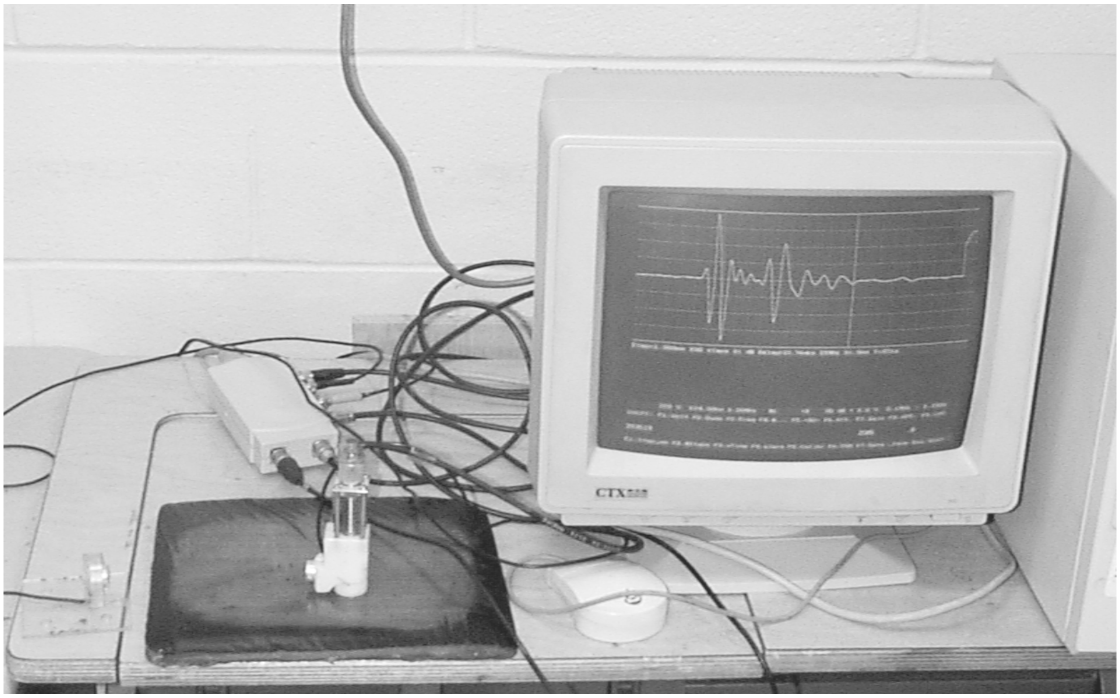


Figure 4.8 - Portable Ultrasonic Hand-held Scanner.

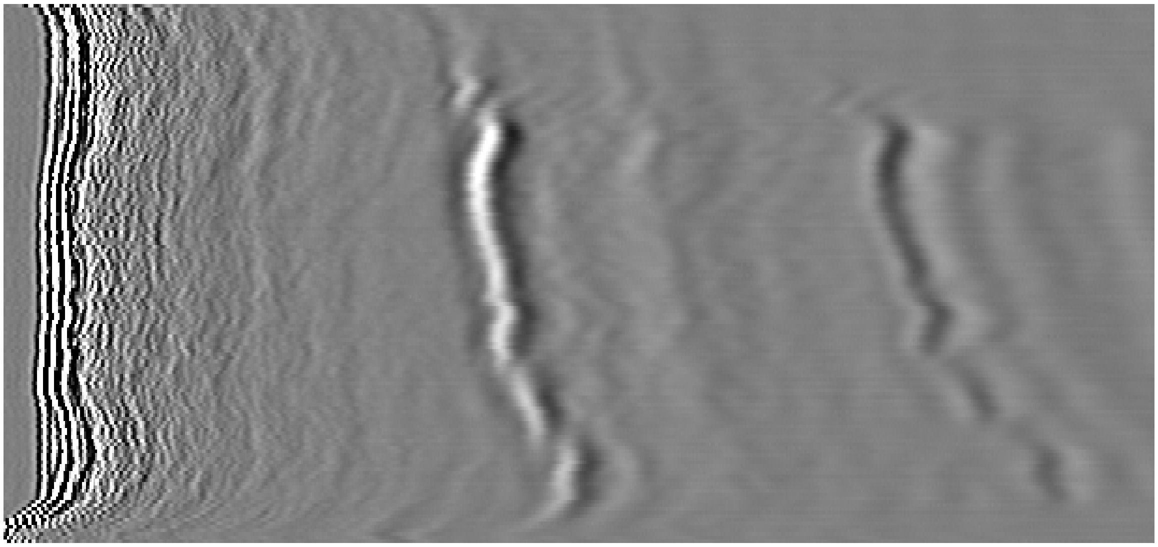


Figure 4.9 - B-scan (cross-section) Image of Composite Bridge Beam after Load Test. Image size is 4" vertical scale and 25 microseconds horizontal scale.

B-scan (cross-section) image of composite bridge beam after load test taken by portable scanner is presented in Figure 4.9. One can see large a delamination at about 0.5" depth.

The wave propagation laboratory has two advanced Laser based ultrasonic vibrometers. That was attached to ultrasonic scanner to test possibility of remote ultrasonic NDT. This way we hope to eliminate need of mechanical scanning and liquid based immersion thus dramatically improve inspection speed.

4.4 THERMOGRAPHIC EQUIPMENT

The thermographic NDT equipment consists of a thermographic camera (Agema), infrared heaters, corresponding regulated power supplies, and mechanical shutters. It has been assembled as shown in Figure 4.10. The primary use will be for adhesive bond inspection in repaired and rehabilitated highway structures.

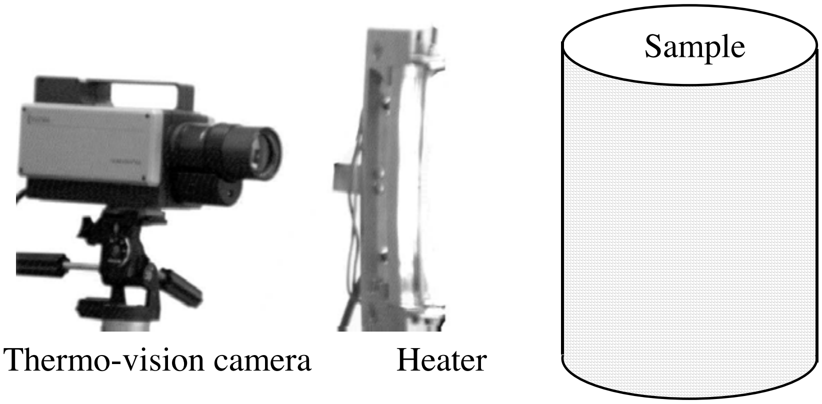


Figure 4.10 - Installation for thermographic NDT of adhesive joint between composite rehabilitation wrap and concrete column.

Chapter 5 – Summary

5.1 SUMMARY

The following is a summary of the results of Tasks 1, 2, and 3 of the work plan. In general the project is within budget and on schedule. The one exception is development of scaled models for primary composite structural members required under Task 2. This issue will be resolved shortly and is not expected to delay completion of the project.

Task 1

1. The task has been completed. The following summarizes the results of this task:
   - i. An extensive literature search has been completed. The results are given in this report and in the accompanying electronic version.
   - ii. Research and professional journals, conference proceedings, and databases available through the construction and highway industry, state departments of transportation, the Department of Defense Nondestructive Testing Information and Analysis Center, and plastics manufacturers and fabricators, have been scanned and relevant abstracts and papers reviewed.
   - iii. A worldwide review of Codes and standards has been undertaken and their relevance assessed. Particular emphasis has been placed on ASTM standards.
   - iv. Existing knowledge about damage evolution under monotonic and fatigue loading has been summarized.
   - v. Procedures for manufacturer and vendor qualification have been reviewed together with test procedures for scaled models. During development of the project proposal the researchers anticipated using the procedure outlined in the American Society of Mechanical Engineers (ASME) RTP-1 standard to qualify fabricators. It has become apparent that this procedure, which requires a fabricator to make a demonstration vessel, is not appropriate for the applications considered under this project
   - vi. Procedures for calibration of nondestructive examination techniques have been reviewed and, as appropriate, will be incorporated into the TxDOT test procedures.
   - vii. Visual inspection is the primary method of nondestructive inspection for structural plastics. Codes and standards published by the ASME are the most relevant to TxDOT structures.
   - viii. Acoustic emission is an important tool for inspection of structural plastics. Codes and standards published by ASTM, ASME, The Society of the Plastics Industry, and the American Society for Nondestructive Testing provide guidance for development of a TxDOT test procedure.
   - ix. A severe limitation of acoustic emission as currently practiced is the inability of the technique to determine the type of flaw giving rise to the emission. Preliminary research has been reported that addresses this problem. Defect signature analysis will be one of the subjects of research under this project.
   - x. Ultrasonic inspection has been widely used for inspection of advanced composites of the type used in the aerospace industry. Though technically challenging, inspection of bonded joints has also been demonstrated.

xi. The aerospace industry experience can be applied to the lower cost composite structures that are envisioned by TxDOT. Economic test techniques and procedures for defect detection and bonded joint inspection are feasible and can be developed.
xii. Dye penetrant inspection is used as an enhancement to visual inspection by a small segment of the composites industry. No published procedures are available but will be prepared as part of this project.
xiii. Thermography has been used to inspect structural plastics in the aerospace industry. The technique will be explored under this project.

Task 2

i. Test specimens for ultrasonic and acoustic emission testing have been acquired and prepared. Special purpose specimens have been fabricated, and full-scale beam and pipe specimens from TxDOT Project 0-1773 have been used.
ii. Specimens include components that are in the "as received" condition, after testing with load induced damage, and with impact damage.
iii. The test samples include glass and carbon fiber, polyester, vinyl ester, and epoxy resin.
iv. Fabrication methods include pultrusion, contact molding, filament winding, and built-up construction from previously cured components. The latter include samples with different percentages of effective bond area.
v. Glass fiber reinforced plastic wrapped concrete specimens have been made available for ultrasonic testing.
vi. Two FRP tanks are being used for thermography experiments.
vii. The scaled models have been defined for concrete with FRP reinforcing bars, and for composite wrapped columns. Representative scaled models for beams and primary structural members are still being explored with TxDOT and fabricators.

Task 3

i. A comprehensive range of acoustic emission test equipment has been assembled. The equipment ranges from digital research instrumentation to equipment used for field testing FRP tanks, pressure vessels, and manlift booms. Instrumentation designed to monitor steel bridges, which was developed under a Federal Highway Administration program has also been made available to the project.
ii. Neural network software for signature analysis of the acoustic emission data has been purchased and time has been allocated on the UT Cray supercomputer to run this program.
iii. A&M has acquired thermovision equipment that can be used on composites.
iv. Digital imaging software of the type used by Dr. Morgan at TxDOT has been purchased. This will assist in correlating visual inspection with a quantitative measure of crack damage.
v. An extensive range of ultrasonic equipment has been acquired, including automated immersion scanners, pulser/receivers, and software for data collection, analysis and A-scan, B-scan, and C-scan displays.
vi. A range of conventional ultrasonic sensors is available and prototype sensors for ultrasonic inspection of composites have been purchased.

vii. Hand scanners have been designed and fabricated. These scanners are intended for field use.
viii. Laser based ultrasonic vibrometers will be used with the ultrasonic scanners to evaluate the possibility of remote ultrasonic inspection.

Appendix A
ASTM Standards

	Designation	ASTM Standard	Property Tested	System
1.	D2143	D2143-94 Standard Test Method for Cyclic Pressure Strength of Reinforced, Thermosetting Plastic Pipe		Composite
2.	D2517	D2517-94 Standard Specification for Reinforced Epoxy Resin Gas Pressure Pipe and Fittings		Composite
3.	C1043.	C1043-97 Standard Practice for Guarded-Hot-Plate Design Using Circular Line-Heat Sources		Composite Matrix Fiber
4.	C1116	C1116-97 Standard Specification for Fiber-Reinforced Concrete and Shotcrete		Concrete
5.	C114	C114-00 Standard Test Methods for Chemical Analysis of Hydraulic Cement		Concrete
6.	C1157	C1157-00 Standard Performance Specification for Hydraulic Cement		Concrete
7.	C1312	C1312-97 Standard Practice for Making and Conditioning Chemical-Resistant Sulfur Polymer Cement Concrete Test Specimens in the Laboratory		Concrete
8.	C1355	C1355/C1355M-96 Standard Specification for Glass Fiber Reinforced Gypsum Composites		Composite
9.	C1438	C1438-99e1 Standard Specification for Latex and Powder Polymer Modifiers for Hydraulic Cement Concrete and Mortar		Concrete
10.	C1439	C1439-99e1 Standard Test Methods for Polymer-Modified Mortar and Concrete		Concrete
11.	C172	C172-99 Standard Practice for Sampling Freshly Mixed Concrete		Concrete
12.	C177	C177-97 Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus		Composite Matrix Fiber
13.	C267	C267-97 Standard Test Methods for Chemical Resistance of Mortars, Grouts, and Monolithic Surfacings and Polymer Concretes	General	Concrete Composite
14.	C294	C294-98 Standard Descriptive Nomenclature for Constituents of Concrete Aggregates	Reference	Concrete
15.	C305	C305-99 Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency		Concrete
16.	C488	C488-83(1998) Standard Test Method for Conducting Exterior Exposure Tests of Finishes for Thermal Insulation	Thermal Insulation	Composite
17.	C494	C494/C494M-99a Standard Specification for Chemical Admixtures for Concrete	Chemical Admixtures	Concrete
	Designation	**ASTM Standard**	**Property Tested**	**System**
18.	C531	C531-00 Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes		Concrete Composite
19.	C579	C579-96 Standard Test Method for Compressive Strength of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings and Polymer Concretes		Concrete Composite

20.	C580	C580-98 Standard Test Method for Flexural Strength and Modulus of Elasticity of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes	General	Concrete Composite
21.	C581	C581-94 Standard Practice for Determining Chemical Resistance of Thermosetting Resins Used in Glass-Fiber-Reinforced Structures Intended for Liquid Service	Chemical Resistance	Matrix
22.	C582	C582-95 Standard Specification for Contact-Molded Reinforced Thermosetting Plastic (RTP) Laminates for Corrosion-Resistant Equipment		Matrix
23.	C905	C905-96 Standard Test Methods for Apparent Density of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes	Apparent Density	Concrete Composite
24.	D1043	D1043-99 Standard Test Method for Stiffness Properties of Plastics as a Function of Temperature by Means of a Torsion Test	Stiffness Properties	Composite Matrix Fiber
25.	D1044	D1044-99 Standard Test Method for Resistance of Transparent Plastics to Surface Abrasion		Composite Matrix Fiber
26.	D1045	D1045-95 Standard Test Methods for Sampling and Testing Plasticizers Used in Plastics		Composite Matrix Fiber
27.	D1201	D1201-99 Standard Specification for Thermosetting Polyester Molding Compounds		Composite
28.	D1242	D1242-95a Standard Test Methods for Resistance of Plastic Materials to Abrasion	Abrasion Resistance	Composite Matrix Fiber
29.	D1435	D1435-99 Standard Practice for Outdoor Weathering of Plastics		Composite Matrix Fiber
30.	D1556	D1556-00 Standard Test Method for Density and Unit Weight of Soil in Place by the Sand-Cone Method		Composite
31.	D1598	D1598-97 Standard Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure		Composite Matrix Fiber
	Designation	**ASTM Standard**	**Property Tested**	**System**
32.	D1599	D1599-99 Standard Test Method for Resistance to Short-Time Hydraulic Failure Pressure of Plastic Pipe, Tubing, and Fittings		Composite
33.	D1600	D1600-99 Standard Terminology for Abbreviated Terms Relating to Plastics		Composite
34.	D1708	D1708-96 Standard Test Method for Tensile Properties of Plastics By Use of Microtensile Specimens	Tensile Properties	Composite Matrix Fiber
35.	D1709	D1709-98 Standard Test Methods for Impact Resistance of Plastic Film by the Free-Falling Dart Method		Composite
36.	D1763	D1763-94 Standard Specification for Epoxy Resins	General	Composite
37.	D1790	D1790-99 Standard Test Method for Brittleness Temperature of Plastic Sheeting by Impact	Brittleness Temperature	Composite
38.	D1822	D1822-99 Standard Test Method for Tensile-Impact Energy to Break Plastics and Electrical Insulating Materials		Composite

39.	D1921	D1921-96 Standard Test Methods for Particle Size (Sieve Analysis) of Plastic Materials		Composite
40.	D1922	D1922-94a Standard Test Method for Propagation Tear Resistance of Plastic Film and Thin Sheeting by Pendulum Method		Composite
41.	D1928	D1928-96 Standard Practice for Preparation of Compression-Molded Polyethylene Test Sheets and Test Specimens		Polyethylene
42.	D1929	D1929-96 Standard Test Method for Determining Ignition Temperature of Plastics	Ignition Temperature	Composite
43.	D1938	D1938-94 Standard Test Method for Tear-Propagation Resistance of Plastic Film and Thin Sheeting by a Single-Tear Method		Composite
44.	D1972	D1972-97 Standard Practice for Generic Marking of Plastic Products		Composite
45.	D2093	D2093-97 Standard Practice for Preparation of Surfaces of Plastics Prior to Adhesive Bonding		Adhesive
46.	D2137	D2137-94(2000) Standard Test Methods for Rubber Property-Brittleness Point of Flexible Polymers and Coated Fabrics	Flexural	Rubber
47.	D2290	D2290-92 Standard Test Method for Apparent Tensile Strength of Ring or Tubular Plastics and Reinforced Plastics by Split Disk Method		Composite

	Designation	**ASTM Standard**	**Property Tested**	**System**
48.	D2291	D2291-98 Standard Practice for Fabrication of Ring Test Specimens for Glass-Resin Composites		Composite
49.	D2343	D2343-95 Standard Test Method for Tensile Properties of Glass Fiber Strands, Yarns, and Rovings Used in Reinforced Plastics	Tensile Properties	Composite
50.	D2344	D2344/D2344M-00 Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates		Composite Matrix Fiber
51.	D2412	D2412-96a Standard Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading		Composite
52.	D2444	D2444-99 Standard Test Method for Determination of the Impact Resistance of Thermoplastic Pipe and Fittings by Means of a Tup (Falling Weight)	Impact Resistance	Matrix
53.	D2471	D2471-99 Standard Test Method for Gel Time and Peak Exothermic Temperature of Reacting Thermosetting Resins		Composite
54.	D2513	D2513-00 Standard Specification for Thermoplastic Gas Pressure Pipe, Tubing, and Fittings		Matrix
55.	D256	D256-97 Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics	Impact Resistance	Composite Matrix Fiber
56.	D2562	D2562-94 Standard Practice for Classifying Visual Defects in Parts Molded from Reinforced Thermosetting Plastics		Composite
57.	D2563	D2563-94 Standard Practice for Classifying Visual Defects in Glass-Reinforced Plastic Laminate Parts	Reference Visual Defects	Composite

58.	D2718	D2718-95 Standard Test Method for Structural Panels in Planar Shear (Rolling Shear)		Matrix
59.	D2719	D2719-89(1994)e1 Standard Test Methods for Structural Panels in Shear Through-the-Thickness		Matrix
60.	D2732	D2732-96 Standard Test Method for Unrestrained Linear Thermal Shrinkage of Plastic Film and Sheeting	Temperature	Composite Matrix Fiber
61.	D2734	D2734-94 Standard Test Methods for Void Content of Reinforced Plastics	Void Content	Composite Matrix Fiber
62.	D2837	D2837-98a Standard Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials		Matrix

	Designation	ASTM Standard	Property Tested	System
63.	D2838	D2838-95 Standard Test Method for Shrink Tension and Orientation Release Stress of Plastic Film and Thin Sheeting		Composite
64.	D2842	D2842-97 Standard Test Method for Water Absorption of Rigid Cellular Plastics		Composite
65.	D2843	D2843-99 Standard Test Method for Density of Smoke from the Burning or Decomposition of Plastics		Composite
66.	D2856	D2856-94(1998) Standard Test Method for Open-Cell Content of Rigid Cellular Plastics by the Air Pycnometer		Composite
67.	D2857	D2857-95 Standard Practice for Dilute Solution Viscosity of Polymers	Viscosity	Composite Matrix Fiber
68.	D2924	D2924-99 Standard Test Method for External Pressure Resistance of "Fiberglass"		Fiber
69.	D2925	D2925-95 Standard Test Method for Beam Deflection of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting Resin) Pipe Under Full Bore Flow		Fiber
70.	D2990	D2990-95 Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics	Creep	Composite Matrix Fiber
71.	D2992	D2992-96e1 Standard Practice for Obtaining Hydrostatic or Pressure Design Basis for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings		Fiber
72.	D2996	D2996-95 Standard Specification for Filament-Wound "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe		Fiber
73.	D2997	D2997-99 Standard Specification for Centrifugally Cast "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe		Fiber
74.	D3028	D3028-95 Standard Test Method for Kinetic Coefficient of Friction of Plastic Solids	Kinetic Coefficient	Composite Matrix Fiber
75.	D3039-D3039M	D3039/D3039M-00 Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials	Tensile Properties	Composite Matrix
76.	D3043	D3043-00 Standard Methods of Testing Structural Panels in Flexure	Flexural	Composite
77.	D3045	D3045-92(1997) Standard Practice for Heat Aging of Plastics Without Load		Composite

	Designation	ASTM Standard	Property Tested	System
78.	D3132	D3132-84(1996) Standard Test Method for Solubility Range of Resins and Polymers	Solubility Range	Composite
79.	D3139	D3139-98 Standard Specification for Joints for Plastic Pressure Pipes Using Flexible Elastomeric Seals		Composite
80.	D3163	D3163-96 Standard Test Method for Determining Strength of Adhesively Bonded Rigid Plastic Lap-Shear Joints in Shear by Tension Loading		Adhesive
81.	D3164	D3164-97 Standard Test Method for Strength Properties of Adhesively Bonded Plastic Lap-Shear Sandwich Joints in Shear by Tension Loading	Strength	Adhesive
82.	D3164M	D3164M-98 Standard Test Method for Strength Properties of Adhesively Bonded Plastic Lap-Shear Sandwich Joints in Shear by Tension Loading (Metric)	Strength Properties	Adhesive
83.	D3165	D3165-00 Standard Test Method for Strength Properties of Adhesives in Shear by Tension Loading of Single-Lap-Joint Laminated Assemblies	Strength Properties	Adhesive
84.	D3166	D3166-99 Standard Test Method for Fatigue Properties of Adhesives in Shear by Tension Loading (Metal/Metal)	Fatigue Properties	Adhesive
85.	D3171	D3171-99 Standard Test Method for Constituent Content of Composite Materials	Constituent Content	Composite
85.	D3262	D3262-96 Standard Specification for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Sewer Pipe		Fiber
87.	D3299	D3299-00 Standard Specification for Filament-Wound Glass-Fiber-Reinforced Thermoset Resin Corrosion-Resistant Tanks		Fiber
88.	D3333	D3333-95 Standard Practice for Sampling Man-Made Staple Fibers, Sliver, or Tow for Testing		Fiber
89.	D3410-D3410M	D3410/D3410M-95 Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading	Compressive Properties	Matrix
90.	D3417	D3417-99 Standard Test Method for Enthalpies of Fusion and Crystallization of Polymers by Differential Scanning Calorimetry (DSC)		Composite Matrix Fiber
91.	D3418	D3418-99 Standard Test Method for Transition Temperatures of Polymers By Differential Scanning Calorimetry	Transition Temperature	Composite Matrix Fiber
92.	D3419	D3419-93 Standard Practice for In-Line Screw-Injection Molding Test Specimens From Thermosetting Compounds		Composite Matrix
93.	D3420	D3420-95 Standard Test Method for Pendulum Impact Resistance of Plastic Film	Impact Resistance	Composite
94.	D3433	D3433-99 Standard Test Method for Fracture Strength in Cleavage of Adhesives in Bonded Joints		Adhesive

95.	D3479-D3479M	D3479/D3479M-96 Standard Test Method for Tension-Tension Fatigue of Polymer Matrix Composite Materials	Fatigue	Matrix
96.	D3499	D3499-94 Standard Test Method for Toughness of Wood-Based Structural Panels	Toughness	Matrix
97.	D3500	D3500-90(1995)e1 Standard Test Methods for Structural Panels in Tension		Matrix
98.	D3501	D3501-94 Standard Test Methods for Wood-Based Structural Panels in Compression	Compression	Matrix
99.	D3517	D3517-96 Standard Specification for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pressure Pipe		Fiber
100.	D3530-3530M	D3530/D3530M-97 Standard Test Method for Volatiles Content of Epoxy Matrix Prepreg	Volatiles Content	Matrix
101.	D3544	D3544-76(1996) Standard Guide for Reporting Test Methods and Results on High Modulus Fibers	Reference	Fiber
102.	D3552-3552M	D3552/D3552M-96 Test Method for Tensile Properties of Fiber-Reinforced Metal Matrix Composites	Tensile Properties	Matrix
103.	D3553	D3553-76(1996) Standard Test Method for Fiber Content by Digestion of Reinforced Metal Matrix Composites		Fiber
104.	D3641	D3641-97 Standard Practice for Injection Molding Test Specimens of Thermoplastic Molding and Extrusion Materials		Composite
105.	D3642	D3642-98 Standard Test Method for Softening Point of Certain Alkali-Soluble Resins	Temperature Softening Point	Composite
106.	D3647	D3647-84(1995) Standard Practice for Classifying Reinforced Plastic Pultruded Shapes According to Composition		Fiber
107.	D3681	D3681-96 Standard Test Method for Chemical Resistance of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe in a Deflected Condition	Resistance	Fiber
108.	D3753	D3753-99 Standard Specification for Glass-Fiber-Reinforced Polyester Manholes and Wetwells		Fiber
109.	D3754	D3754-96 Standard Specification for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Sewer and Industrial Pressure Pipe		Fiber

	Designation	**ASTM Standard**	**Property Tested**	**System**
110.	D3763	D3763-99 Standard Test Method for High Speed Puncture Properties of Plastics Using Load and Displacement Sensors		Composite Matrix Fiber
111.	D3795	D3795-00 Standard Test Method for Thermal Flow, Cure, and Behavior Properties of Pourable Thermosetting Materials by Torque Rheometer	General	Composite
112.	D3814	D3814-99 Standard Guide for Locating Combustion Test Methods for Polymeric Materials	Reference	Composite Matrix Fiber
113.	D3826	D3826-98 Standard Practice for Determining Degradation End Point in Degradable Polyethylene and Polypropylene Using a Tensile Test		Composite Matrix Fiber

114.	D3835	D3835-96 Standard Test Method for Determination of Properties of Polymeric Materials by Means of a Capillary Rheometer	Reference	Composite Matrix Fiber
115.	D3839	D3839-94a Standard Practice for Underground Installation of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe	General	Fiber
116.	D3840	D3840-99 Standard Specification for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe Fittings for Nonpressure Applications		Fiber
117.	D3841	D3841-97 Standard Specification for Glass-Fiber-Reinforced Polyester Plastic Panels	General	Composite
118.	D3846	D3846-94 Standard Test Method for In-Plane Shear Strength of Reinforced Plastics		Composite
119.	D3878	D3878-98 Standard Terminology Composite Materials	Reference	Composite
120.	D3887	D3887-96 Standard Specification for Tolerances for Knitted Fabrics	General	Composite
121.	D3914	D3914-96 Standard Test Method for In-Plane Shear Strength of Pultruded Glass-Reinforced Plastic Rod		Fiber
122.	D3916	D3916-94 Standard Test Method for Tensile Properties of Pultruded Glass-Fiber-Reinforced Plastic Rod	Tensile	Fiber
123.	D3917	D3917-96 Standard Specification for Dimensional Tolerance of Thermosetting Glass-Reinforced Plastic Pultruded Shapes		Matrix
124.	D3918	D3918-96 Standard Terminology Relating to Reinforced Plastic Pultruded Products	Reference	Fiber
125.	D3929	D3929-96e1 Standard Test Method for Evaluating the Stress Cracking of Plastics by Adhesives Using the Bent-Beam Method	Tensile	Composite Matrix Fiber
126.	D3935	D3935-94 Standard Specification for Polycarbonate (PC) Unfilled and Reinforced Material		Composite
	Designation	**ASTM Standard**	**Property Tested**	**System**
127.	D3965	D3965-99 Standard Specification for Rigid Acrylonitrile-Butadiene-Styrene (ABS) Materials for Pipe and Fittings		ABS
128.	D3981	D3981-95 Standard Specification for Polyethylene Films Made from Medium-Density Polyethylene for General Use and Packaging Applications		Matrix
129.	D3982	D3982-98 Standard Specification for Contact Molded "Fiberglass" (Glass Fiber Reinforced Thermosetting Resin) Duct and Hoods	General	Fiber
130.	D3983	D3983-98 Standard Test Method for Measuring Strength and Shear Modulus of Nonrigid Adhesives by the Thick-Adherend Tensile-Lap Specimen	Strength	Adhesive
131.	D4000	D4000-00 Standard Classification System for Specifying Plastic Materials	Reference	Composite Matrix Fiber
132.	D4001	D4001-93(1999) Standard Test Method for Determination of Weight-Average Molecular Weight of Polymers By Light Scattering	Weight	Composite Matrix Fiber
133.	D4018	D4018-99 Standard Test Methods for Properties of Continuous Filament Carbon and Graphite Fiber Tows	General	Fiber

134.	D4019	D4019-94a Standard Test Method for Moisture in Plastics by Coulometric Regeneration of Phosphorus Pentoxide	Moisture	Composite Matrix Fiber
135.	D4020	D4020-00 Standard Specification for Ultra-High-Molecular-Weight Polyethylene Molding and Extrusion Materials	Reference	Matrix
136.	D4027	D4027-98 Standard Test Method for Measuring Shear Properties of Structural Adhesives by the Modified-Rail Test		Adhesives
137.	D4029	D4029-97 Standard Specification for Finished Woven Glass Fabrics	Reference	Composite
138.	D4065	D4065-95 Standard Practice for Determining and Reporting Dynamic Mechanical Properties of Plastics		Composite Matrix Fiber
139.	D4066	D4066-99 Standard Classification System for Nylon Injection and Extrusion Materials (PA)	Reference	Nylon
140.	D4067	D4067-96 Standard Specification for Reinforced and Filled Polyphenylene Sulfide (PPS) Injection Molding and Extrusion Materials	Reference	PPS
141.	D4092	D4092-96 Standard Terminology Relating to Dynamic Mechanical Measurements on Plastics	Reference Dynamic	Composite Matrix Fiber
	Designation	**ASTM Standard**	**Property Tested**	**System**
142.	D4093	D4093-95 Standard Test Method for Photoelastic Measurements of Birefringence and Residual Strains in Transparent or Translucent Plastic Materials	General	Composite Matrix Fiber
143.	D4097	D4097-95ae3 Standard Specification for Contact-Molded Glass-Fiber-Reinforced Thermoset Resin Corrosion-Resistant Tanks		Composite
144.	D4101	D4101-99 Standard Specification for Propylene Plastic Injection and Extrusion Materials	Reference	Composite Matrix Fiber
145.	D4102	D4102-82(1999) Standard Test Method for Thermal Oxidative Resistance of Carbon Fibers	Temperature Resistance	Fiber
146.	D4103	D4103-90(1995)e1 Standard Practice for Preparation of Substrate Surfaces for Coefficient of Friction Testing		Composite
147.	D412	D412-98a Standard Test Methods for Vulcanized Rubber and Thermoplastic Rubbers and Thermoplastic Elastomers-Tension		Rubber
148.	D413	D413-98 Standard Test Methods for Rubber Property-Adhesion to Flexible Substrate		Rubber
149.	D4141	D4141-95 Standard Practice for Conducting Accelerated Outdoor Exposure Tests of Coatings		Composite
150.	D4166	D4166-99 Standard Test Method for Measurement of Thickness of Nonmagnetic Materials by Means of a Digital Magnetic Intensity Instrument	Thickness	Composite Matrix Fiber
151.	D4167	D4167-97 Standard Specification for Fiber-Reinforced Plastic Fans and Blowers		Fiber
152.	D4204	D4204-00 Standard Practice for Preparing Plastic Film Specimens for a Round-Robin Study		Composite Matrix Fiber

153.	D4216	D4216-00 Standard Specification for Rigid Poly (Vinyl Chloride) (PVC) and Related PVC and Chlorinated Poly (Vinyl Chloride) (CPVC) Building Products Compounds		PVC
154.	D4218	D4218-96 Standard Test Method for Determination of Carbon Black Content in Polyethylene Compounds By the Muffle-Furnace Technique		Polyethylene
155.	D4226	D4226-99 Standard Test Methods for Impact Resistance of Rigid Poly(Vinyl Chloride) (PVC) Building Products	Resistance	PVC
156.	D4255	D4255/D4255M-83(1994)e1 Standard Guide for Testing In-plane Shear Properties of Composite Laminates		Composite

	Designation	**ASTM Standard**	**Property Tested**	**System**
157.	D4263	D4263-83(1999) Standard Test Method for Indicating Moisture in Concrete by the Plastic Sheet Method	Moisture	Concrete
158.	D4272	D4272-99 Standard Test Method for Total Energy Impact of Plastic Films By Dart Drop		Composite Matrix Fiber
159.	D430	D430-95 Standard Test Methods for Rubber Deterioration-Dynamic Fatigue	Fatigue	Rubber
160.	D4329	D4329-99 Standard Practice for Fluorescent UV Exposure of Plastics		Composite
161.	D4350	D4350-95 Standard Test Method for Corrosivity Index of Plastics and Fillers	Corrosion	Composite Matrix Fiber
162.	D4357	D4357-96 Standard Specification for Plastic Laminates Made from Woven-Roving and Woven-Yarn Glass Fabrics		Composite
163.	D4364	D4364-94 Standard Practice for Performing Outdoor Accelerated Weathering Tests of Plastics Using Concentrated Sunlight		Composite Matrix Fiber
164.	D4385	D4385-95 Standard Practice for Classifying Visual Defects in Thermosetting Reinforced Plastic Pultruded Products		Composite Matrix Fiber
165.	D4389	D4389-99 Standard Specification for Finished Glass Fabrics Woven From Rovings		Fiber
166.	D4398	D4398-95 Standard Test Method for Determining the Chemical Resistance of Fiberglass-Reinforced Thermosetting Resins by One-Side Panel Exposure	Resistance	Fiber
167.	D4440	D4440-95a Rheological Measurement of Polymer Melts Using Dynamic Mechanical Procedures		Composite
168.	D4473	D4473-95a Standard Practice for Measuring the Cure Behavior of Thermosetting Resins Using Dynamic Mechanical Procedures	Cure	Composite
169.	D4475	D4475-96 Standard Test Method for Apparent Horizontal Shear Strength of Pultruded Reinforced Plastic Rods By The Short-Beam Method	Shear	Composite
170.	D4476	D4476-97 Standard Test Method for Flexural Properties of Fiber Reinforced Pultruded Plastic Rods	Flexural	Matrix Composite
171.	D4501	D4501-95 Standard Test Method for Shear Strength of Adhesive Bonds Between Rigid Substrates by the Block-Shear Method	Shear	Adhesive

172.	D4526	D4526-96 Standard Practice for Determination of Volatiles in Polymers by Static Headspace Gas Chromatography	Volatile Content	Composite Matrix Fiber
	Designation	**ASTM Standard**	**Property Tested**	**System**
173.	D4549	D4549-98 Standard Specification for Polystyrene Molding and Extrusion Materials (PS)	Reference	Composite Matrix Fiber
174.	D4703	D4703-93 Standard Practice for Compression Molding Thermoplastic Materials into Test Specimens, Plaques, or Sheets	Moldability	Composite Matrix Fiber
175.	D4762	D4762-88(1995)e1 Standard Guide for Testing Automotive/Industrial Composite Materials	Reference	Composite
176.	D4796	D4796-88(1998) Standard Test Method for Bond Strength of Thermoplastic Traffic Marking Materials	Adhesion	Composite Matrix Fiber
177.	D4804	D4804-98 Standard Test Methods for Determining the Flammability Characteristics of Nonrigid Solid Plastics	Flammability	Composite Matrix Fiber
178.	D4805	D4805-88(1994)e1 Standard Terminology for Plastics Standards	Reference	Composite Matrix Fiber
179.	D4812	D4812-99 Standard Test Method for Unnotched Cantilever Beam Impact Strength of Plastics	Impact Resistance	Composite Matrix Fiber
180.	D4853	D4853-97 Standard Guide for Reducing Test Variability	Variability	Test Methods
181.	D4867	D4867/D4867M-96 Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures	Moisture and Tensile Strength	Concrete
182.	D4923	D4923-92 Standard Specification for Reinforced Thermosetting Plastic Poles	Deflection Bending Torsional Fatigue	Composite
183.	D4935	D4935-99 Standard Test Method for Measuring the Electromagnetic Shielding Effectiveness of Planar Materials	Electro-magnetic Shielding	Composite Matrix Fiber
184.	D4968	D4968-00 Standard Guide for Annual Review of Test Methods and Specifications for Plastics	Committee Review	Composite Matrix Fiber
185.	D4969	D4969-97 Standard Specification for Polytetrafluoroethylene-(PTFE) Coated Glass Fabric	General	Composite
186.	D4974	D4974-99 Standard Test Method for Thermal Shrinkage of Yarn and Cord Using a Thermal Shrinkage Oven	Thermal Shrinkage	Composite Matrix Fiber
	Designation	**ASTM Standard**	**Property Tested**	**System**
187.	D4976	D4976-00 Standard Specification for Polyethylene Plastics Molding and Extrusion Materials	General	Composite Matrix Fiber
188.	D5023	D5023-99 Standard Test Method for Measuring the Dynamic Mechanical Properties of Plastics Using Three Point Bending	Viscoelastic	Composite Matrix Fiber

189.	D5024	D5024-95a Standard Test Method for Measuring the Dynamic Mechanical Properties of Plastics in Compression	Viscoelastic in Compression	Composite Matrix Fiber
190.	D5026	D5026-95a Standard Test Method for Measuring the Dynamic Mechanical Properties of Plastics in Tension	Viscoelastic in Tension	Composite Matrix Fiber
191.	D5028	D5028-96 Standard Test Method for Curing Properties of Pultrusion Resins by Thermal Analysis	Curing	Composite Matrix Fiber
192.	D5041	D5041-98 Standard Test Method for Fracture Strength in Cleavage of Adhesives in Bonded Joints	Fracture Strength in Cleavage	Matrix
193.	D5045	D5045-99 Standard Test Methods for Plane-Strain Fracture Toughness and Strain Energy Release Rate of Plastic Materials	Plane-Strain Fracture Toughness and Strain Energy	Composite Matrix Fiber
194.	D5083	D5083-96 Standard Test Method for Tensile Properties of Reinforced Thermosetting Plastics Using Straight-Sided Specimens	Tensile	Composite
195.	D5179	D5179-98 Standard Test Method for Measuring Adhesion of Organic Coatings to Plastic Substrates by Direct Tensile Testing	Coating Adhesion	Composite Matrix Fiber
196.	D5203	D5203-98 Standard Specification for Polyethylene Plastics Molding and Extrusion Materials from Recycled Post-Consumer (HDPE) Sources	General	Recycled Composite Matrix Fiber
197.	D5224	D5224-93 Standard Practice for Compression Molding Test Specimens of Thermosetting Molding Compounds	Tensile	Composite Matrix Fiber
198.	D5225	D5225-98 Standard Test Method for Measuring Solution Viscosity of Polymers with a Differential Viscometer	Viscosity	Composite Matrix Fiber
	Designation	**Title**	**Property Tested**	**System**
199.	D5226	D5226-98 Standard Practice for Dissolving Polymer Materials	Dissolving	Composite Matrix Fiber
200.	D5229	D5229/D5229M-92(1998)e1 Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials	Moisture Absorption	Composite
201.	D5279	D5279-99 Standard Test Method for Measuring the Dynamic Mechanical Properties of Plastics in Torsion	Viscoelastic in Torsion	Composite Matrix Fiber
202.	D5300	D5300-93 Standard Test Method for Measurement of Resin Content and Other Related Properties of Polymer Matrix Thermoset Prepreg by Combined Mechanical and Ultrasonic Methods	General	Composite
203.	D5319	D5319-97 Standard Specification for Glass-Fiber Reinforced Polyester Wall and Ceiling Panels	General Semistructural	Composite

	Designation	ASTM Standard	Property Tested	System
204.	D5365	D5365-99 Standard Test Method for Long-Term Ring-Bending Strain of "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe	Ring Bending Strain	Composite
205.	D5418	D5418-99 Standard Test Method for Measuring the Dynamic Mechanical Properties of Plastics Using a Dual Cantilever Beam	Dynamic Mechanical	Composite Matrix Fiber
206.	D5420	D5420-98a Standard Test Method for Impact Resistance of Flat, Rigid Plastic Specimen by Means of a Striker Impacted by a Falling Weight (Gardner Impact)	Impact Resistance	Composite Matrix Fiber
207.	D5421	D5421-93 Standard Specification for Contact Molded "Fiberglass" (Glass-Fiber-Reinforced Thermosetting Resin) Flanges		Composite Matrix
208.	D5422	D5422-93 Standard Test Method for Measurement of Properties of Thermoplastic Materials by Screw-Extrusion Capillary Rheometer		Composite Matrix
209.	D543	D543-95 Standard Practices for Evaluating the Resistance of Plastics to Chemical Reagents		Composite Matrix Plastic-Fiber
210.	D5437	D5437 Practice for Weathering of Plastics Under Marine Floating Exposure (Discontinued 1999) , Replaced By No Replacement		Composite Matrix Plastic-Fiber
211.	D5448	D5448/D5448M-93 Standard Test Method for Inplane Shear Properties of Hoop Wound Polymer Matrix Composite Cylinders		Composite
212.	D5449	D5449/D5449M-93 Standard Test Method for Transverse Compressive Properties of Hoop Wound Polymer Matrix Composite Cylinders		Composite
213.	D5450	D5450/D5450M-93 Standard Test Method for Transverse Tensile Properties of Hoop Wound Polymer Matrix Composite Cylinders		Composite
214.	D5467	D5467-97 Standard Test Method for Compressive Properties of Unidirectional Polymer Matrix Composites Using a Sandwich Beam		Composite
215.	D5477	D5477-95 Standard Practice for Identification of Polymer Layers or Inclusions by Fourier Transform Infrared Microspectroscopy (FT-IR)		Matrix
216.	D5491	D5491-98 Standard Classification for Recycled Post-Consumer Polyethylene Film Sources for Molding and Extrusion Materials		Matrix
217.	D5510	D5510-94 Standard Practice for Heat Aging of Oxidatively Degradable Plastics		Composite Matrix
218.	D5528	D5528-94a Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites		Composite
219.	D5538	D5538-98 Standard Practice for Thermoplastic Elastomers-Terminology and Abbreviations		Matrix
220.	D5573	D5573-99 Standard Practice for Classifying Failure Modes in Fiber-Reinforced-Plastic (FRP) Joints		Composite

221.	D5592	D5592-94 Standard Guide for Material Properties Needed in Engineering Design Using Plastics	Gold	Composite Matrix Fiber
222.	D5628	D5628-96 Standard Test Method for Impact Resistance of Flat, Rigid Plastic Specimens by Means of a Falling Dart (Tup or Falling Mass)		Composite Matrix
223.	D5687	D5687/D5687M-95 Standard Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation	Gold	Composite
224.	D5744	D5744-96 Standard Test Method for Accelerated Weathering of Solid Materials Using a Modified Humidity Cell		ORES
225.	D5766	D5766/D5766M-95 Standard Test Method for Open Hole Tensile Strength of Polymer Matrix Composite Laminates		Composite
226.	D578	D578-00 Standard Specification for Glass Fiber Strands		Fiber
227.	D5813	D5813-95 Standard Specification for Cured-In-Place Thermosetting Resin Sewer Pipe		Composite Matrix
228.	D5824	D5824-98 Standard Test Method for Determining Resistance to Delamination of Adhesive Bonds in Overlay-Wood Core Laminates Exposed to Heat and Water		Wood

	Designation	**ASTM Standard**	**Property Tested**	**System**
229.	D5868	D5868-95 Standard Test Method for Lap Shear Adhesion for Fiber Reinforced Plastic (FRP) Bonding		Composite Glue
230.	D5870	D5870-95 Standard Practice for Calculating Property Retention Index of Plastics		Composite Matrix
231.	D5948	D5948-96e1 Standard Specification for Molding Compounds, Thermosetting		Composite Matrix
232.	D5961	D5961/D5961M-96 Standard Test Method for Bearing Response of Polymer Matrix Composite Laminates		Composite
233.	D6048	D6048-96 Standard Practice for Stress Relaxation Testing of Raw Rubber, Unvulcanized Rubber Compounds, and Thermoplastic Elastomers		Matrix Fiber
234.	D6049	D6049-96 Standard Test Method for Rubber Property--Measurement of the Viscous and Elastic Behavior of Unvulcanized Raw Rubbers and Rubber Compounds by Compression Between Parallel Plates		Rubber
235.	D6068	D6068-96 Standard Test Method for Determining J-R Curves of Plastic Materials		Composite Matrix
236.	D6108	D6108-97 Standard Test Method for Compressive Properties of Plastic Lumber and Shapes		Matrix
237.	D6109	D6109-97 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastic Lumber		Composite Matrix
238.	D6110	D6110-97 Standard Test Methods for Determining the Charpy Impact Resistance of Notched Specimens of Plastics		Matrix
239.	D6111	D6111-97 Standard Test Method for Bulk Density and Specific Gravity of Plastic Lumber and Shapes by Displacement		Composite Matrix

240.	D6112	D6112-97 Standard Test Methods for Compressive and Flexural creep and Creep-Rupture of Plastic Lumber and Shapes		Matrix
241.	D6115	D6115-97 Standard Test Method for Mode I Fatigue Delamination Growth Onset of Unidirectional Fiber-Reinforced Polymer Matrix Composites		Composite Matrix
242.	D6117	D6117-97 Standard Test Methods for Mechanical Fasteners In Plastic Lumber and Shapes		Mechanical Fasteners
243.	D6132	D6132-97 Standard Test Method for Nondestructive Measurement of Dry Film Thickness of Applied Organic Coatings Over Concrete Using an Ultrasonic Gage		Composite Matrix
	Designation	**ASTM Standard**	**Property Tested**	**System**
244.	D6147	D6147-97 Test Method for Vulcanized Rubber and Thermoplastic Elastomer-Determination of Force Decay (Stress Relaxation) in Compression		Matrix
245.	D618	D618-99 Standard Practice for Conditioning Plastics for Testing	Gold	Composite Matrix
246.	D6194	D6194-97 Standard Test Method for Glow-Wire Ignition of Materials		Matrix Composite Fiber
247.	D6264	D6264-98 Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer-Matrix Composite to a Concentrated Quasi-Static Indentation Force	Gold	Composite
248.	D6272	D6272-98 Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulting Materials by Four-Point Bending	Gold	Composite Matrix
249.	D6275	D6275-98 Standard Practice for Laboratory Testing of Bridge Decks		Bridge Deck
250.	D6289	D6289-98 Standard Test Method for Measuring Shrinkage from Mold Dimensions of Molded Thermosetting Plastics		Composite Matrix
251.	D6341	D6341-98 Standard Test Method for Determination of the Linear Coefficient of Thermal Expansion of Plastic Lumber and Plastic Lumber Shapes Between -30 and 140°F (-34.4 and 60°C)		Matrix Composite Fiber
252.	D635	D635-98 Standard Test Method for Rate of Burning and/or Extent and Time of Burning of Plastics in a Horizontal Position		Composite Matrix Fiber
253.	D6370	D6370-99 Standard Test Method for Rubber-Compositional Analysis by Thermogravimetry (TGA)		Rubber
254.	D6372	D6372-99a Standard Practice for Design, Testing, and Construction of Micro-Surfacing		Composite
255.	D638	D638-99 Standard Test Method for Tensile Properties of Plastics	Gold	Composite Matrix
256.	D6395	D6395-99 Standard Test Method for Flatwise Flexural Impact Resistance of Rigid Plastics		Composite Matrix
257.	D6415	D6415-99 Standard Test Method for Measuring the Curved Beam Strength of a Fiber-Reinforced Polymer-Matrix Composite		Composite

	Designation	ASTM Standard	Property Tested	System
258.	D6416	D6416-99 Standard Test Method for Two-Dimensional Flexural Properties of Simply Supported Sandwich Composite Plates Subjected to a Distributed Load		Composite
259.	D6435	D6435-99 Standard Test Method for Shear Properties of Plastic Lumber and Plastic Lumber Shapes	Gold	Matrix
260.	D6436	D6436-99 Standard Guide for Reporting Properties for Plastics and Thermoplastic Elastomers	Gold	Composite Matrix
261.	D648	D648-98c Standard Test Method for Deflection Temperature of Plastics under Flexural Load in the Edgewise Position		Matrix
262.	D6484	D6484-99 Standard Test Method for Open-Hole Compressive Strength of Polymer Matrix Composite Laminates	Gold	Composite
263.	D6507	D6507-00 Standard Practice for Fiber Reinforcement Orientation Codes for Composite Materials	Gold	Composite
264.	D669	D669-92(1997) Standard Test Method for Dissipation Factor and Permittivity Parallel with Laminations of Laminated Sheet and Plate Materials		Composite
265.	D671	D671-93 Standard Test Method for Flexural Fatigue of Plastics by Constant-Amplitude-of-Force	Gold	Composite Matrix
266.	D695	D695-96 Standard Test Method for Compressive Properties of Rigid Plastics		Composite Matrix
267.	D696	D696-98 Standard Test Method for Coefficient of Linear Thermal Expansion of Plastics Between -30°C and 30°C With a Vitreous Silica Dilatometer	Gold	Matrix Composite
268.	D709	D709-00 Standard Specification for Laminated Thermosetting Materials		Composite
269.	D732	D732-99 Standard Test Method for Shear Strength of Plastics by Punch Tool		Composite Matrix
270.	D746	D746-98 Standard Test Method for Brittleness Temperature of Plastics and Elastomers by Impact	Gold	Composite Matrix
271.	D747	D747-99 Standard Test Method for Apparent Bending Modulus of Plastics by Means of a Cantilever Beam		Matrix
272.	D785	D785-98 Standard Test Method for Rockwell Hardness of Plastics and Electrical Insulating Materials		Matrix
273.	D790	D790-99 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials		Composite Matrix
274.	D792	D792-98 Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement		Matrix
275.	D883	D883-99 Standard Terminology Relating to Plastics	Gold	Composite Matrix
276.	D953	D953-95 Standard Test Method for Bearing Strength of Plastics	Gold	Composite Matrix

277.	D955	D955-89(1996) Standard Test Method for Measuring Shrinkage from Mold Dimensions of Molded Plastics		Matrix
278.	E1012	E1012-99 Standard Practice for Verification of Specimen Alignment Under Tensile Loading		Composite Matrix Fiber
279.	E1067	E1067-96 Standard Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels		Plastic Tanks
280.	E1118	E1118-95 Standard Practice for Acoustic Emission Examination of Reinforced Thermosetting Resin Pipe (RTRP)		Composite
281.	E1131	E1131-98 Standard Test Method for Compositional Analysis by Thermogravimetry		Composite Matrix Fiber
282.	E1175	E1175-87(1996) Standard Test Method for Determining Solar or Photopic Reflectance, Transmittance, and Absorptance of Materials Using a Large Diameter Integrating Sphere	Gold	Composite Matrix Fiber
283.	E1208	E1208-99 Standard Test Method for Fluorescent Liquid Penetrant Examination Using the Lipophilic Post-Emulsification Process		Matrix
284.	E1209	E1209-99 Standard Test Method for Fluorescent Liquid Penetrant Examination Using the Water-Washable Process		Matrix
285.	E1210	E1210-99 Standard Test Method for Fluorescent Liquid Penetrant Examination Using the Hydrophilic Post-Emulsification Process	Gold	Matrix
286.	E1219	E1219-99 Standard Test Method for Fluorescent Liquid Penetrant Examination Using the Solvent-Removable Process		Matrix
287.	E1220	E1220-99 Standard Test Method for Visible Liquid Penetrant Examination Using the Solvent-Removable Process		Matrix
288.	E1225	E1225-99 Standard Test Method for Thermal Conductivity of Solids by Means of the Guarded-Comparative-Longitudinal Heat Flow Technique		Composite Matrix Fiber
289.	E1252	E1252-98 Standard Practice for General Techniques for Qualitative Infrared Analysis	Gold	Composite Matrix
	Designation	**ASTM Standard**	**Property Tested**	**System**
290.	E1269	E1269-99 Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry		Composite Matrix
291.	E1309	E1309-00 Standard Guide for Identification of Fiber-Reinforced Polymer-Matrix Composite Materials in Databases		Electrodes
292.	E1417	E1417-99 Standard Practice for Liquid Penetrant Examination		Non-Porous Matrix
293.	E1418	E1418-98 Standard Test Method for Visible Penetrant Examination Using the Water-Washable Process		Non-Porous Matrix
294.	E1441	E1441-97 Standard Guide for Computed Tomography (CT) Imaging	Gold	Composite Matrix Fiber
295.	E1495	E1495-97 Standard Guide for Acousto-Ultrasonic Assessment of Composites, Laminates, and Bonded Joints		Composite

296.	E1556	E1556-98 Standard Specification for Epoxy Resin System for Composite Skin, Honeycomb Sandwich Panel Repair		Composite Matrix
297.	E1570	E1570-00 Standard Practice for Computed Tomographic (CT) Examination	Gold	Composite Matrix Fiber
298.	E1582	E1582-93 Standard Practice for Calibration of Temperature Scale for Thermogravimetry		Composite Matrix Fiber
299.	E1640	E1640-99 Standard Test Method for Assignment of the Glass Transition Temperature By Dynamic Mechanical Analysis		Matrix Fiber
300.	E165	E165-95 Standard Test Method for Liquid Penetrant Examination		Non-Porous Matrix
301.	E1672	E1672-95 Standard Guide for Computed Tomography (CT) System Selection	Gold	System Selection
302.	E1740	E1740-95 Standard Test Method for Determining the Heat Release Rate and Other Fire-Test-Response Characteristics of Wallcovering Composites Using a Cone Calorimeter		Composite Matrix Fiber
303.	E1765	E1765-98 Standard Practice for Applying Analytical Hierarchy Process (AHP) to Multiattribute Decision Analysis of Investments Related to Buildings and Building Systems	Gold	Investing
304.	E1820	E1820-99a Standard Test Method for Measurement of Fracture Toughness		Metals
	Designation	**ASTM Standard**	**Property Tested**	**System**
305.	E1881	E1881-97 Standard Guide for Cell Culture Analysis with SIMS		Cell Culture
306.	E1888	E1888-97 Standard Test Method for Acoustic Emission Testing of Pressurized Containers Made of Fiberglass Reinforced Plastic with Balsa Wood Cores		Pressurized Containers
307.	E1952	E1952-98 Standard Test Method for Thermal Conductivity and Thermal Diffusivity by Modulated Temperature Differential Scanning Calorimetry		Non-Porous Matrix Fiber
308.	E2015	E2015-99 Standard Guide for Preparation of Plastics and Polymeric Specimens for Microstructural Examination		Composite Matrix Fiber
309.	E2041	E2041-99 Standard Method for Estimating Kinetic Parameters by Differential Scanning Calorimeter Using the Borchardt and Daniels Method		Composite Matrix
310.	E2070	E2070-00 Standard Test Method for Kinetic Parameters by Differential Scanning Calorimetry Using Isothermal Methods		Composite Matrix
311.	E2076	E2076-00 Standard Test Method for Examination of Fiberglass Reinforced Plastic Fan Blades Using Acoustic Emission		Composite
312.	E328	E328-86(1996)e1 Standard Test Methods for Stress Relaxation Tests for Materials and Structures		Composite Matrix Fiber
313.	E606	E606-92(1998) Standard Practice for Strain-Controlled Fatigue Testing		Matrix
314.	E831	E831-00 Standard Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis		Composite Matrix Fiber

	Designation	ASTM Standard	Property Tested	System
315.	F1164	F1164-97 Standard Test Method for Evaluation of Transparent Plastics Exposed to Accelerated Weathering Combined with Biaxial Stress		Matrix
316.	F1173	F1173-95 Standard Specification for Thermosetting Resin Fiberglass Pipe and Fittings to be Used for Marine Applications		Composite
317.	F1251	F1251-89(1995) Standard Terminology Relating to Polymeric Biomaterials in Medical and Surgical Devices		Matrix
318.	F1474	F1474-98 Standard Test Method for Slow Crack Growth Resistance of Notched Polyethylene Plastic Pipe		Matrix
319.	F1488	F1488-00 Standard Specification for Coextruded Composite Pipe		Composite
320.	F1579	F1579-98 Standard Specification for Polyaryletherketone (PAEK) Resins for Surgical Implant Applications		Matrix
321.		F1581-99 Standard Specification for Composition of Anorganic Bone for Surgical Implants		Anorganic Bone
322.	F1588	F1588-96 Standard Test Method for Constant Tensile Load Joint Test (CTLJT)		Matrix Composite
323.	F1589	F1589-95 Standard Test Method for Determination of the Critical Pressure for Rapid Crack Propagation in Plastic Pipe		Polyethelene Pipe
324.	F1618	F1618-96 Standard Practice for Determination of Uniformity of Thin Films on Silicon Wafers		Thin Metal Coating
325.	F1634	F1634-95 Standard Practice for In-Vitro Environmental Conditioning of Polymer Matrix Composite Materials and Implant Devices		Composite
326.	F1635	F1635-95 Standard Test Method for In Vitro Degradation Testing of Poly (L-lactic Acid) Resin and Fabricated Form for Surgical Implants		Matrix
327.	F1668	F1668-96 Standard Guide for Construction Procedures for Buried Plastic Pipe		Composite
328.	F1675	F1675-96 Standard Practice for Life-Cycle Cost Analysis of Plastic Pipe Used for Culverts, Storm Sewers, and Other Buried Conduits		Composite Matrix
329.	F1839	F1839-97 Standard Specification for Rigid Polyurethane Foam for Use as a Standard Material for Testing Orthopaedic Devices and Instruments		Rigid Polyurethane
330.	F1855	F1855-98 Standard Specification for Polyoxymethylene (Acetal) for Medical Applications		Acetal;
331.	F1876	F1876-98 Standard Specification for Polyetherketoneetherketoneketone (PEKEKK) Resins for Surgical Implant Applications		Pekekk
332.	F451	F451-99a Standard Specification for Acrylic Bone Cement		Acrylic Cement

333.	F561	F561-97 Practice for Retrieval and Analysis of Implanted Medical Devices, and Associated Tissues		Handling of Implanted Medical Devices
334.	F602	F602-98a Standard Criteria for Implantable Thermoset Epoxy Plastics		Matrix
335.	F604	F604-94 Standard Specification for Silicone Elastomers Used in Medical Applications		Silicone Elastomers
336.	F624	F624-98a Standard Guide for Evaluation of Thermoplastic Polyurethane Solids and Solutions for Biomedical Applications		Thermoplastic Polyurethane
	Designation	**ASTM Standard**	**Property Tested**	**System**
337.	F639	F639-98a Standard Specification for Polyethylene Plastics for Medical Applications		Polyethylene Plastics
338.	F640	F640-79(1994)e1 Standard Test Methods for Radiopacity of Plastics for Medical Use		Composite Matrix
339.	F641	F641-98a Standard Specification for Implantable Epoxy Electronic Encapsulants		Epoxy Electronic Encapsulents
340.	F648	F648-98 Standard Specification for Ultra-High-Molecular-Weight Polyethylene Powder and Fabricated Form for Surgical Implants		Ultra-High-Molecular-Weight Polyethylene Powder
341.	F665	F665-98 Standard Classification for Vinyl Chloride Plastics Used in Biomedical Application		Vinyl Chloride Plastics
342.	F702	F702-98a Standard Specification for Polysulfone Resin for Medical Applications		Polysulfone Resin
343.	F755	F755-99 Standard Specification for Selection of Porous Polyethylene for Use in Surgical Implants		Porous Polyethylene
344.	F981	F981-99 Standard Practice for Assessment of Compatibility of Biomaterials for Surgical Implants with Respect to Effect of Materials on Muscle and Bone		Biomaterials
345.	F997	F997-98a Standard Specification for Polycarbonate Resin for Medical Applications		Polycarbonate Resin
346.	D5379	D5379/D5379M-98 Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method		Composite
347.	E1417	E1417-99 Standard Practice for Liquid Penetrant Examination		Low Porosity Matrix
348.	D1238	D1238-99 Standard Test Method for Melt Flow Rates of Thermoplastics by Extrusion Plastometer		Fiber
349.	D2240	D2240-97 Standard Test Method for Rubber Property-Durometer Hardness		Rubber

350.	D2583	D2583-95 Standard Test Method for Indention Hardness of Rigid Plastics by Means of a Barcol Impressor		Fiber
351.	D570	D570-98 Standard Test Method for Water Absorption of Plastics		Composite Matrix Fiber
	Designation	**ASTM Standard**	**Property Tested**	**System**
352.	D149	D149-97a Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies		Fiber
353.	C522	C522-87 Standard Test Method for Airflow Resistance of Acoustical Materials		Fiber
354.	E1050	Standard Test Method for Impedance and Absorption of Acoustical Materials Using A Tube, Two Microphones and A Digital Frequency Analysis System		Fiber
355.	C423	Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method		Fiber
356.	E90	Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements		Fiber
357.	C518	Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus		Fiber
358.	C335	Standard Test Method for Steady-State Heat Transfer Properties of Horizontal Pipe Insulation		Fiber
359.	C1114	Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus		Fiber
360.	E84	Standard Test Method for Surface Burning Characteristics of Building Materials		Fiber
361.	E136	Standard Test Method for Behavior of Materials in a Vertical Tube Furnace		Fiber
362.	D2247	Standard Practice for Testing Water Resistance of Coatings in 100% Relative Humidity		Matrix
363.	E104	Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions		Matrix
364.	D1141	Standard Practice for the Preparation of Substitute Ocean Water		Matrix

Appendix B
Property Map of ASTM Standards

SYSTEM	PROPERTY	ASTM STANDARD DESIGNATION
MATRIX	**MECHANICAL**	
	tensile strength	D638
	percent elongation	D638
	modulus of elasticity	D638
	secant modulus	D638
	Poisson's ratio	D638
	compressive strength	D695
	compressive yield strength	D695
	offset yield strength	D695
	modulus of elasticity	D695
	shear strength	D732
	shear modulus	D732
	flexural strength	D790
	flexural modulus	D790
	rockwell (hardness)	D785/E 140-84/DIN 50150/ISO 4964
	shore/barcol	D2240/D2583
	chemical resistance	C581
	resistance	D1044
	resistance to abrasion	D1242
	impact resistance film	D1709
	tensile impact energy	D1822
	izod pendulum impact resistance	D256
	THERMAL	
	apparent modulus of rigidity	D
	brittleness temperature	D1790
	ignition temperature	D1929
	peak exothermic temperature	D2471
	crystallization temperature	D3418
	glass transition temperature	D3418
	melting temperature	D3418
	deflection temperature under flexural load	D648
	PHYSICAL	
	coefficient of linear thermal expansion	D696
	thermal conductivity	C177
	specific gravity (relative density)	D792
	water absorption	D570
	dielectric strength	D149
	particle size	D1921
MATRIX	**PHYSICAL**	
	theoretical density	D2734
	void content	D2734
	apparent conditioned density	C905
	relative viscosity	D2857 / ISO 1628/1

	kinetic coefficient of friction	D3028
	solubility range	D3132
	volatiles content	D3530/D3530M
	glass transition temperature	D3418
	moisture absorption	D5229
	ENVIRONMENTAL	
	water resistance	D2247/E104
	saltwater resistance	D1141/C581
	alkali resistance	C581
	dry heat resistance	D3045
FIBER	**MECHANICAL**	
	tensile strength	D638
	percent elongation	D638
	modulus of elasticity	D638
	secant modulus	D638
	Poisson's ratio	D638
	compressive strength	D695
	compressive yield strength	D695
	offset yield strength	D695
	modulus of elasticity	D695
	shear strength	D732
	shear modulus	D732
	flexural strength	D790
	flexural modulus	D790
	rockwell	D785
	shore/barcol	D2240/D2583
	chemical resistance	C581
	resistance	D1044
	resistance to abrasion	D1242
	impact resistance film	D1709
	THERMAL	
	tensile impact energy	D1822
	izod pendulum impact resistance	D256

SYSTEM	PROPERTY	ASTM STANDARD DESIGNATION
FIBER	**THERMAL**	
	apparent modulus of rigidity	D
	brittleness temperature	D1790
	ignition temperature	D1929
	peak exothermic temperature	D2471
	crystallization temperature	D3418
	glass transition temperature	D3418
	melting temperature	D3418
	deflection temperature under flexural load	D648
	PHYSICAL	
	coefficient of linear thermal expansion	D696
	thermal conductivity	C177

	filament diameter	
	specific gravity	D792
	water absorption	D570
	dielectric strength	D149
	particle size	D1921
	theoretical density	D2734
	void content	D2734
	apparent conditioned density	C905
	relative viscosity	D2857 / ISO 1628/1
	kinetic coefficient of friction	D3028
	solubility range	D3132
	volatiles content	D3530/D3530M
	glass transition temperature	D3418
COMPOSITE	**MECHANICAL**	
	tensile strength	D638
	percent elongation	D638
	modulus of elasticity	D638
	secant modulus	D638
	Poisson's ratio	D638
	compressive strength	D695
	compressive yield strength	D695
	offset yield strength	D695
	modulus of elasticity	D695
	shear strength	D732
	shear modulus	D732
	flexural strength	D790

SYSTEM	**PROPERTY**	**ASTM STANDARD DESIGNATION**
COMPOSITE	**MECHANICAL**	
	flexural modulus	D790
	rockwell	D785
	shore/barcol	D2240/D2583
	chemical resistance	C581
	resistance	D1044
	resistance to abrasion	D1242
	impact resistance film	D1709
	tensile impact energy	D1822
	izod pendulum impact resistance	D256
	THERMAL	
	apparent modulus of rigidity	D
	brittleness temperature	D1790
	ignition temperature	D1929
	peak exothermic temperature	D2471
	crystallization temperature	D3418
	glass transition temperature	D3418
	melting temperature	D3418
	deflection temperature under flexural load	D648
	coefficient of linear thermal expansion	D696
	thermal conductivity	C177

	PHYSICAL	
	specific gravity	D792
	water absorption	D570
	dielectric strength	D149
	particle size	D1921
	theoretical density	D2734
	void content	D2734
	apparent conditioned density	C905
	relative viscosity	D2857 / ISO 1628/1
	kinetic coefficient of friction	D3028
	solubility range	D3132
	constituent content	D3171
	volatiles content	D3530/D3530M
	glass transition temperature	D3418
	fiber volume fraction	D3171
	void volume fraction	D2734
	moisture diffusivity	D696

SYSTEM	PROPERTY	ASTM STANDARD DESIGNATION
COMPOSITE	**PHYSICAL**	
	dimensional stability	E831
	density	D792
	ELECTRICAL	
	dielectric strength	D149
	permittivity	D150
	dry arc resistance	D495
	liquid contamination	D2303

Appendix C
Non-ASTM Standards

	Organization	**Designation**	**Title**
1.	American Society of Mechanical Engineers	ASME SEC X MA APP 4	Appendix 4 - Mandatory Glossary of Terms Related to Fiber-Reinforced Plastics
2.	British Standards Institution	BSI BS EN 2561	1995 Carbon Fibre Reinforced Plastics - Unidirectional Laminates - Tensile Test Parallel to the Fibre Direction
3.	British Standards Institution	BSI BS EN 2563	1997 Carbon Fibre Reinforced Plastics - Unidirectional Laminates - Determination of the Apparent Interlaminar Shear Strength
4.	British Standards Institution	BSI BS ISO 11667	1997 Fibre Reinforced Plastics - Moulding Compounds and Prepregs - Determination of Resin, Reinforcement-Fibre and Mineral-Filler Content Dissolution Methods
5.	Chinese National Standards	BSMI K6097500	General Rules for Methods of Test for Glass Fiber Reinforced Plastics
6.	Chinese National Standards	BSMI K6097600	Method of Test for Fiber Content of Glass Fiber Reinforced Plastics
7.	Chinese National Standards	BSMI K6097800	Method of Test for Tensile Properties of Glass Fiber Reinforced Plastics
8.	Chinese National Standards	BSMI K6097900	Method of Test for Flexural Properties of Glass Fiber Reinforced Plastics
9.	Chinese National Standards	BSMI K6098000	Method of Test for Compressive Properties of Glass Fiber Reinforced Plastics
10.	Chinese National Standards	BSMI K6098100	Method of Test for Apparent Interlaminal Shear Strength of Glass Fiber Reinforced Plastics
11.	Chinese National Standards	BSMI K6098200	Method of Test for Transverse Shear Strength of Glass Fiber Reinforced Plastics
12.	Chinese National Standards	BSMI K6098400	Method of Test for Barcol Hardness of Glass Fiber Reinforced Plastics
13.	Chinese National Standards	BSMI K6102900	Method of Test for Tensile Properties of Carbon Fiber Reinforced Plastics
14.	Chinese National Standards	BSMI K6103000	Method of Test for Flexural Properties of Carbon Fiber Reinforced Plastics
15.	Chinese National Standards	BSMI K6103100	Method of Test for Fiber Content and Void Content of Carbon Fiber Reinforced Plastics
16.	Chinese National Standards	BSMI K6103300	Method of Test for Apparent Interlaminar Shear Strength of Carbon Fiber Reinforced Plastics
17.	China Standards Information Centre	CSIC GB/T 1446-83	The generals of test methods for properties of fiber-reinforced plastics
18.	China Standards Information Centre	CSIC GB/T 1447-83	Test method for tensile properties of glass fiber-reinforced plastics
	Organization	**Designation**	**Title**
19.	China Standards Information Centre	CSIC GB/T 1448-83	Test method for compressive properties of glass fiber-reinforced plastics
20.	China Standards Information Centre	CSIC GB/T 1449-83	Test method for flexural properties of glass fiber-reinforced plastics
21.	China Standards Information Centre	CSIC GB/T 1450.1-83	Test method for interlaminar shear strength of glass fiber-reinforced plastics
22.	China Standards Information Centre	CSIC GB/T 1450.2-83	Test method for the punch-type of strength of glass fiber-reinforced plastics
23.	China Standards Information Centre	CSIC GB/T 1451-83	Test method for the Charpy impact resistance of glass fiber-reinforced plastics

24.	China Standards Information Centre	CSIC GB/T 1462-88	Test methods for water absorption of fiber reinforced plastics
25.	China Standards Information Centre	CSIC GB/T 1463-88	Test methods for density and relative density of fiber reinforced plastics
26.	China Standards Information Centre	CSIC GB/T 2572-81	Glass fiber reinforced plastics-Average linear expansion factor of fiber-Method of testing
27.	China Standards Information Centre	CSIC GB/T 2573-89	Test method for atmosphere exposure of glass fiber reinforced plastics
28.	China Standards Information Centre	CSIC GB/T 2574-89	Test method for resistance of glass fiber reinforced plastics to damp heat
29.	China Standards Information Centre	CSIC GB/T 2575-89	Test method for resistance of glass fiber reinforced plastics to water
30.	China Standards Information Centre	CSIC GB/T 2576-89	Test method for insoluble matter content of resin used in fiber reinforced plastics
31.	China Standards Information Centre	CSIC GB/T 2577-89	Test method for resin content of glass fiber reinforced plastics
32.	China Standards Information Centre	CSIC GB/T 3140-95	Test method for mean specific heat capacity of fiber reinforced plastics
33.	China Standards Information Centre	CSIC GB/T 3355-82	Test method for longitudinal transverse shear (L-T shear)properties of fiber reinforced plastics

	Organization	**Designation**	**Title**
34.	China Standards Information Centre	CSIC GB/T 3365-82	Test method for void content of carbon fiber reinforced plastics by microscopy
35.	China Standards Information Centre	CSIC GB/T 3366-96	Test method for fiber volume content of carbon fiber reinforced plastics
36.	China Standards Information Centre	CSIC GB/T 3854-83	Test method for hardness of fiber reinforced plastics by means of Barcol impressor
37.	China Standards Information Centre	CSIC GB/T 3855-83	Test method for resin content of carbon fiber reinforced plastics
38.	China Standards Information Centre	CSIC GB/T 3856-83	Test method for compression properties of unidirectional fiber reinforced plastics
39.	China Standards Information Centre	CSIC GB/T 3857-87	Test method for chemical resistance of glass fiber reinforced thermosetting plastics
40.	China Standards Information Centre	CSIC GB/T 3961-93	Terms for fiber reinforced plastics
41.	China Standards Information Centre	CSIC GB/T 6011-85	Test method for flammability characteristics of fiber-reinforced plastics--Incandescent rod method
42.	China Standards Information Centre	CSIC GB/T 8237-87	Liquid unsaturated polyester resin for glass fiber reinforced plastics
43.	China Standards Information Centre	CSIC GB/T 8924-88	Test method for flammability characteristics of glass fiber reinforced plastics using the oxygen index method

44.	China Standards Information Centre	CSIC GB/T 9979-88	Guide rule of test for mechanical properties of fiber-reinforced plastics at elevated and reduced temperatures
45.	China Standards Information Centre	CSIC GB/T 10703-89	Test method accelerated for resistance of glass fiber reinforced plastics to water
46.	Army research Laboratory, Weapons and Materials	MIL-HDBK-17 -1E	Polymer Matrix Composites Volume 1. Guidelines for Characterization of Structural Materials
47.	Army research Laboratory, Weapons and Materials	MIL-HDBK-17 -2E	Composite Materials Handbook Volume 2. Polymer Matrix Composites Materials Properties
48.	Army research Laboratory, Weapons and Materials	MIL-HDBK-17 -3E	Polymer Matrix Composites Volume 3. Materials Usage, Design, and Analysis
	Organization	**Designation**	**Title**
49.	International Organization for Standardization	ISO 15733	Fine Ceramics (Advanced Ceramics, Advanced Technical Ceramics) - Test Method for Tensile Stress-Strain Behaviour of Continuous, Fibre-Reinforced Composites at Room Temperature First Edition
50.	Army research Laboratory, Weapons and Materials	MIL-HDBK-731 Valid Notice 1	Nondestructive Testing Methods of Composite Materials - Thermography
51.	Army research Laboratory, Weapons and Materials	MIL-HDBK-731	Nondestructive Testing Methods of Composite Materials - Thermography
52.	Army research Laboratory, Weapons and Materials	MIL-HDBK-732A	Nondestructive Testing Methods of Composite Materials Acoustic Emission
53.	Army research Laboratory, Weapons and Materials	MIL-HDBK-732	Nondestructive Testing Methods of Composite Materials Acoustic Emission
54.	Army research Laboratory, Weapons and Materials	MIL-HDBK-733 Valid Notice 1	Nondestructive Testing Methods of Composite Materials - Radiography
55.	Army research Laboratory, Weapons and Materials	MIL-HDBK-733	Nondestructive Testing Methods of Composite Materials - Radiography
56.	Army research Laboratory, Weapons and Materials	MIL-HDBK-793	Nondestructive Testing Techniques for Structural Composites
57.	Standards Engineering Society	SFS SFS-EN ISO 527-4	Plastics. Determination of tensile properties. Part 4: Test conditions for isotropic and orthotropic fibre-reinforced plastic composites (ISO 527-4:1997)
58.	Standards Engineering Society	SFS SFS-EN ISO 527-5	Plastics. Determination of tensile properties. Part 5: Test conditions for unidirectional fibre-reinforced plastic composites (ISO 527-5:1997)
59.	Standards Engineering Society	SFS SFS-EN ISO 14125	Fibre-reinforced plastic composites. Determination of flexural properties (ISO 14125:1998)
60.	Standards Engineering Society	SFS SFS-EN ISO 14126	Fibre-reinforced plastic composites. Determination of compressive properties in the in-plane direction (ISO 14126:1999)
61.	Standards Engineering Society	SFS SFS-EN ISO 14129	Fibre-reinforced plastic composites. Determination of the in-plane shear stress/shear strain response, including the in-plane shear modulus and strength, by the +/- 45 tension test method (ISO 14129:1997)
62.	Standards Engineering Society	SFS SFS-EN ISO 14130	Fibre-reinforced plastic composites. Determination of apparent interlaminar shear strength by short-beam method (ISO 14130:1997)

	Organization	Designation	Title
63.	British Standards Institution	BSI BS 2782: PT 3: METH 326F	1997 Plastics - Determination of Tensile Properties Part 4: Test Conditions for Isotropic and Orthotropic Fibre-Reinforced Plastic Composites Also Numbered as BS EN 527-4: 1997; (V)
64.	British Standards Institution	BSI BS 2782: PT 3: METH 326G	1997 Plastics - Determination of Tensile Properties Part 5: Test Conditions for Isotropic and Orthotropic Fibre-Reinforced Plastic Composites Also Numbered as BS EN 527-5: 1997; (V)
65.	European Committee for Standardization	CEN PREN 13706-1	Reinforced Plastic Composites - Specification for Pultruded Profiles - Part 1: Designation
66.	European Committee for Standardization	CEN PREN 13706-2	Reinforced Plastic Composites - Specification for Pultruded Profiles - Part 2: Methods of Test and General Requirements
67.	European Committee for Standardization	CEN PREN 13706-3	Reinforced Plastic Composites - Specification for Pultruded Profiles - Part 3: Specific Requirements
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75.	European Committee for Standardization	CEN PREN ISO 14130	Fibre Reinforced Plastic Composites - Determination of Apparent Interlaminar Shear Strength by Short Beam Method (ISO/DIS 14130:1994)

	Organization	Designation	Title
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77.	Gosudarstvennye Standarty State Standard GOST (Russian)	GOST 50579-93 R	Polymer Composites. Classification
78.	Gosudarstvennye Standarty State Standard GOST (Russian)	GOST 50583-93 R	Polymer Composites. List of Properties
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82.	International Organization for Standardization	ISO 14126	Fibre-Reinforced Plastic Composites - Determination of Compressive Properties in the In-Plane Direction First Edition; Replaces ISO 8515: 1991
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84.	International Organization for Standardization	ISO 14130	Fibre-Reinforced Plastic Composites - Determination of Apparent Interlaminar Shear Strength by Short-Beam Method First Edition
85.	International Organization for Standardization	ISO 15034	Composites - Prepregs - Determination of Resin Flow First Edition
86.	International Organization for Standardization	ISO 15040	Composites - Prepregs - Determination of Gel Time First Edition
87.	International Organization for Standardization	ISO 15310	Fibre-Reinforced Plastic Composites - Determination of the In-Plane Shear Modulus by the Plate Twist Method First Edition
88.	Plastics Technical Evaluation Center	PLASTEC R24	Weathering of Glass Reinforced Plastics

	Organization	Designation	Title
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92.	Suppliers of Advanced Composite Materials Assoc.	SACMA SRM 4	Tensile Properties of Oriented Fiber-Resin Composites
93.	Suppliers of Advanced Composite Materials Assoc.	SACMA SRM 5	Open-Hole Tensile Properties of Oriented Fiber-Resin Composites
94.	Suppliers of Advanced Composite Materials Assoc.	SACMA SRM 7	Inplane Shear Stress- Strain Properties of Oriented Fiber-Resin Composites
95.	Suppliers of Advanced Composite Materials Assoc.	SACMA SRM 8	Apparent Interlaminar Shear Strength of Oriented Fiber-Resin Composites by the Short-Beam Method
96.	Suppliers of Advanced Composite Materials Assoc.	SACMA SRM 9	Bearing Strength Properties of Oriented Fiber-Resin Composites (Pending)
97.	Suppliers of Advanced Composite Materials Assoc.	SACMA SRM 10	Calculation of Fiber Volume of Composite Test Laminates
98.	Plastics Technical Evaluation Center	PLASTEC 24651	Fatigue Properties of 8 oz-8 Shaft "E" Fiber Glass Satin Reinforced Epoxies and Polyesters
99.	Federal Aviation Administration	FAA-CT-85/6 Volume I	Fiber Composite Analysis and Design Volume 1 Composite Materials and Laminates
100.	Federal Aviation Administration	FAA-CT-88/18 Volume II	Fiber Composite Analysis and Design Volume II Structures
101.	Composite Can and Tube Institute	CCTI C-120	Water Vapor Permeability Composite Cans (Reviewed and Reapproved September 1985)
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105.	International Organization for Standardization	ISO 37	Rubber, Vulcanized or Thermoplastic - Determination of Tensile Stress-Strain Properties Third Edition
106.	International Organization for Standardization	ISO 48	Rubber, Vulcanized or Thermoplastic - Determination of Hardness (Hardness Between 10 IRHD and 100 IRHD) Third Edition; Amendment 1: 08-15-1999
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108.	International Organization for Standardization	ISO 188	Rubber, Vulcanized or Thermoplastic - Accelerated Ageing and Heat Resistance Tests Third Edition
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112.	International Organization for Standardization	ISO 1827	Rubber, Vulcanized or Thermoplastic - Determination of Modulus in Shear or Adhesion to Rigid Plates - Quadruple Shear Method Second Edition
113.	International Organization for Standardization	ISO 1853	Conducting and Dissipative Rubbers, Vulcanized or Thermoplastic - Measurement of Resistivity Second Edition
114.	International Organization for Standardization	ISO 6505	Rubber, Vulcanized or Thermoplastic - Determination of Tendency to Adhere to and to Corrode Metals Second Edition
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118.	International Organization for Standardization	ISO 14126	Fibre-Reinforced Plastic Composites - Determination of Compressive Properties in the In-Plane Direction First Edition; Replaces ISO 8515: 1991
119.	International Organization for Standardization	ISO 14129	Fibre-Reinforced Plastic Composites - Determination of the In -Plane Shear Stress/Shear Strain Response, Including the In-Plane Shear Modulus and Strength, by the Plus or Minus 45 Degrees Tension Test Method First Edition
120.	International Organization for Standardization	ISO 14130	Fibre-Reinforced Plastic Composites - Determination of Apparent Interlaminar Shear Strength by Short-Beam Method First Edition
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Appendix D
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Appendix E
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Appendix F
References Relating to Acoustic Emission

NATIONAL STANDARDS AND CODES

Each of the following includes procedures and/or evaluation criteria for acoustic emission based inspection and structural evaluation.

1. “Procedure for Acoustic Emission Evaluation of Tank Cars and IM101 Tanks, Issue 5,” Association of American Railroads, Mechanical Division, Washington, DC.

2. “Procedure for Structural Integrity Inspection of Tank Cars Using Acoustic Emission”, Association of American Railroads, Washington, DC, Issue 1-Revision 1, March 2001

3. ASME Section V, Article 11, “ Acoustic Emission Examination of Fiber Reinforced Plastic Vessels, Boiler and Pressure Vessel Code,” American Society of Mechanical Engineers, New York, NY.

4. ASME Section X, “Acceptance Test Procedure for Class II Vessels, Article RT-6, Section X, Boiler and Pressure Vessel Code,” American Society of Mechanical Engineers, New York, NY.

5. ASME RTP-1, “Reinforced Thermoset Plastic Corrosion Resistant Equipment”, American Society of Mechanical Engineers, New York, NY.

6. “Recommended Practice for Acoustic Emission Testing of Fiberglass Reinforced Plastic Resin (RP) Tanks/Vessels”, The Committee on Acoustic Emission from Reinforced Plastics (CARP) of the Composites Institute, The Society of the Plastics Industry, New York, August 1987.

7. “Recommended Practice for Acoustic Emission Evaluation of Fiber Reinforced Plastic (FRP) Tanks and Pressure Vessels,” The Committee on Acoustic Emission for Reinforced Plastics (CARP), A Division of the Technical Council of The American Society for Nondestructive Testing, Inc., Columbus, Ohio, Draft I, October 1999.

8. “MONPAC-PLUS Procedure for Acoustic Emission Testing of Metal Tanks/Vessels”, Monsanto Company, St. Louis, Missouri, Draft D, August 1992.

9. “Procedure for Acoustic Emission Evaluation of Naval Crane Shafts”, The University of Texas at Austin, April 1998.

10. “Procedure for Acoustic Emission Monitoring of Prestressed Concrete Girders” The University of Texas at Austin, May 2001.

11. “Recommended Practice for Acoustic Emission Testing of Pressurized Highway Tankers Made of Fiberglass Reinforced Plastic with Balsa Cores”, American Society for Nondestructive Testing, Columbus, Ohio, 1993.

RELEVANT ASTM STANDARDS

The following standards provide basic calibration, set-up, and guidance for acoustic emission inspection of structural members.

12. E569 Standard Practice for Acoustic Emission Monitoring of Structures During Controlled Stimulation.

13. E650 Standard Guide for Mounting Piezoelectric Acoustic Emission Sensors.

14. E750 Standard Practice for Measuring Operating characteristic of Acoustic Emission Instrumentation.

15. E976 Standard Guide for Determining the Reproducibility of Acoustic Emission Sensor Response.

16. E1067 Standard Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels.

17. E1118 Standard Practice for Acoustic Emission Examination of Reinforced Thermosetting Resin Pipe (RTRP).

18. E1316 Standard Terminology for Nondestructive Examinations.

19. E2075 Standard Practice for Verifying the Consistency of AE-Sensor Response Using an Acrylic Rod.

20. F914 Standard Test Method for Acoustic Emission for Insulated Aerial Personnel Devices.

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24. "Recommended Practice for Acoustic Emission Testing of Reinforced Thermosetting Resin Pipe (RTRP)", First International Symposium on Acoustic Emission from Reinforced Plastics, Reinforced Plastics/Composites Institute, The Society of the Plastics Industry, Inc., New York, 1983.

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    Summary: The authors used the amplitude vs. duration graph to classify the type of damages. Waveform analysis also is included in this paper.

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    Summary: The use of non-accumulative amplitude distribution

30. Berthelot, J.M., and Billaud, J., 1983, “Analysis of the Fracture Mechanisms in Discontinuous Fibre Composites Suing Acoustic Emission,” First International Symposium on Acoustic Emission from Reinforced Composites, The Society of the Plastics Industry, Inc., July 19-21, Session 2, pp.1-10.
    Summary: The use of non-cumulative amplitude distribution. Each peak can tell different failure mechanism in FRP.

31. Berthelot, J.M., and Rhazi, J., 1986, “Different Types of Amplitude Distributions in Composite Materials,” Second International Symposium on Acoustic Emission from Reinforced Composites, The Society of the Plastics Industry, Inc., Reinforced Plastics/Composites Institute, Montreal, Canada, July 21-25, pp.96-103.
    Summary: The use of amplitude distribution method. They found that the amplitude distribution could appear in 3 different shapes - discontinuous, continuous, and intermediate distribution.

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    Summary: The use of non-cumulative amplitude distribution, load vs. accumulative event, and onset of AE in various amplitude ranges.

33. Favre, J.P., and Laizet, J.C., 1989, “Acoustic Analysis of the Accumulation of Cracks in CFRP Cross-Ply Laminates Under Tensile Loading,” Third International Symposium on Acoustic Emission from Composite Materials AECM-3, Paris, France, July 17-21, pp.278-285.
Summary: The paper presents the correlation between high-amplitude AE signals and the number of observed cracks and damage propagation.

34. Gorman, M.R., and Foral, R.F., 1986, “Acoustic Emission Studies of Fiber/Resin Double Cantilever Beam Specimens,” Second International Symposium on Acoustic Emission from Reinforced Composites, The Society of the Plastics Industry, Inc., Reinforced Plastics/Composites Institute, Montreal, Canada, July 21-25, pp.104-109.
Summary: The use of non-cumulative amplitude distribution on glass/epoxy and graphite/peek composites.

35. Gorman, M.R., and Rytting, T.H., 1983, “Long Duration AE Events in Filament Wound Graphite/Epoxy in the 100-300 KHz Band Pass Region,” First International Symposium on Acoustic Emission from Reinforced Composites, The Society of the Plastics Industry, Inc., July 19-21, Session 6, pp.1-5.
Summary: The paper concludes that matrix cracking gives long duration events (LDE’s) which associates with high amplitude (90+). Good or bad sample can be classified from the number of LDE’s and how early they appear.

36. Guild, F.J., et. al., 1983, “Amplitude Distribution Analysis of Acoustic Emission from Composites: The development of a Data Collection and Procession System,” First International Symposium on Acoustic Emission from Reinforced Composites, The Society of the Plastics Industry, Inc., July 19-21, Session 5, pp.1-7.
Summary: The authors suggest other parameters to consider including cumulative event count by amplitude range and differential event count by amplitude range.

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Summary: The use of non-cumulative amplitude distribution, total event count, event count rate, and amplitude distribution at low stress levels.

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Summary: Uses waveform parameters including average slope of wave rise for a high performance composite.

40. Kwon, O., and Yoon, D.J., 1989, “Energy Distribution Analysis of Acoustic Emission Signals from the Tensile Testing of CFRP,” Third International Symposium on Acoustic Emission from Composite Materials AECM-3, Paris, France, July 17-21, pp.298-303.
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Summary: The authors used spectral analysis, Hilbert transform analysis of discrete-time signals, waveform shape, and signal energy to differentiate the damages from delamination and tensile test.

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Summary: The waveform analysis of fiber rupture and matrix dislocation.

45. Pollock, A.A., 1978, “Physical Interpretation of AE/MA Signal Procession,” Second Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials, Pennsylvania State University, November 13-15.
Summary: The paper presents a triple-peaked normal amplitude distribution from fiberglass composite.

46. Ramirez, G., 1999, "Monitoring and Prediction of Damage in Filament Wound Composite Pipes Under Pressure Loading", Dissertation presented for degree of Doctor of Philosophy, The University of Texas at Austin.
Summary: Presents data from pipes as fabricated and with impact damage.

47. Roman, I., et. al., 1986, "Mechanical Behavior and Acoustic Emission Characterization of Kevlar-Epoxy Composites Loaded in Tension," Second International Symposium on Acoustic Emission from Reinforced Composites, The Society of the Plastics Industry, Inc., Reinforced Plastics/Composites Institute, Montreal, Canada, July 21-25. pp.85-89.
Summary: The use of count rate and C-ratio (ratio of hits above 65 dB to hits below 65 dB).

48. Shiwa, M., et. al., 1986, "Acoustic Emission during Tensile, Loading-Holding, and Unloading-Reloading Testing in Fiberglass-Epoxy Composites," Second International Symposium on Acoustic Emission from Reinforced Composites, The Society of the Plastics Industry, Inc., Reinforced Plastics/Composites Institute, Montreal, Canada, July 21-25. pp.44-49.
Summary: The authors compared amplitude distribution between notched and unnotched specimens.

49. Surrel, Y., and Vautrin, A., 1989, "Acoustic Emission Amplitude Analysis by Logarithmic Rate Cartography," Third International Symposium on Acoustic Emission from Composite Materials AECM-3, Paris, France, July 17-21, pp.365-374.
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Summary: Time effects to the Zweben's Theory.

51. Williams, J.H., Lee, S.S., 1978, "Acoustic Emission Monitoring of Fiber Composite Materials and Structures," Journal of Composite Materials, Vol. 12, pp.348-370.
Summary: The use of several diagrams including AE count rate, cumulative AE count, and broken fiber numbers. Paper also concludes that fiber breaks generate high amplitude bursts.

52. Ziehl, P. H., 2000, "Development of a Damage Based Design Criterion for Fiber Reinforced Vessels", Dissertation presented for degree of Doctor of Philosophy, The University of Texas at Austin.
Summary: Proposes a new design method based on onset of acoustic emission.

ANALYSIS OF FAILURE MECHANISMS IN FIBER REINFORCED PLASTIC

53. McGowan, P.T., 1983, “Analysis of Failure Mechanisms in Glass Fiber Reinforced Plastic and Acoustic Emission Correlation with a Transverse Resin Crack Model,” First International Symposium on Acoustic Emission from Reinforced Composites, The Society of the Plastics Industry, Inc., July 19-21, Session 3, pp.1-12.
    Summary: The paper explains the evolution of failure mechanisms in FRP.

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DATA ANALYSIS USING NEURAL NETWORKS AND PATTERN RECOGNITION

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    Summary: Using Linear Learning Machine, Kth nearest neighbor, and SIMCA techniques to recognize AE from different FRP materials.

58. Chen, H.L., and Chen, C.L., 1992, “Applying Neural Network to Acoustic Emission Signal Processing,” Forth International Symposium on Acoustic Emission from Composite Materials AECM-4, Seattle, WA, July 27-31, pp.273-281.
    Summary: The authors studied the neural network to classify and also to predict the ultimate strength of the timber specimens.

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    Summary: Using neural network back propagation to predict the ultimate burst pressure of filament wound graphite/epoxy bottles with two of them have simulated anomalies.

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Summary: Analysis of acoustic emission signals with a neural network.

61. Hill, E.v.K., Israel, P.L., and Knotts, G.L., 1993, "Neural Network Prediction of Aluminum-Lithium Weld Strengths from Acoustic Emission Amplitude Data," Materials Evaluation, Vol.51, No.9, September 1993, pp.1040-1045.
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63. Promboon, Y., 2000, "Acoustic Emission Source Location", Dissertation presented for degree of Doctor of Philosophy, The University of Texas at Austin.
Summary: Preliminary study of neural network based method of source location in composites.

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64. Duke Jr., J.C., and Horne, M.R., 1998, "NDE of Polymeric Composite Material Bridge Components," Structural Material Technology.
Summary: The development of NDE methods including AE for long-term pultruded vinyl ester carbon/glass fiber reinforced bridge beams.

65. Duke Jr., J.C., Horne, M.R., and Johnson, A., 1998, "Baseline NDE of Pultruded Composite Bridge Beams," ICCI 2 Presentation WTR, Tucson, AZ.
Summary: The paper describes baseline AE evaluation of pultruded vinyl ester carbon/glass fiber reinforced bridge beams before being installing in the field.

66. Duke Jr., J.C., Lesko, J., and Weyers, R., 1996, "Nondestructive Evaluation of Critical Composite Material Structural Elements," Nondestructive Evaluation of Bridges and Highways, SPIE 2946, pp.206-210.
Summary: The development of NDE methods including AE for long-term pultruded vinyl ester carbon/glass fiber reinforced bridge beams.

67. Lesko, J., et.al., 1998, "Laboratory & Field Characterization of the Tom's Creek Bridge Composite Superstructure," ICCI 2 Presentation WTR, Tucson, AZ.
Summary: Lab and field test of full-scale pultruded vinyl ester carbon/glass fiber reinforced bridge with timber deck.

DATA ANALYSIS BASED ON ACOUSTIC EMISSION WAVE FORMS FROM WIDE BAND SENSORS

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