DEVELOPMENT OF TEST METHODS FOR TEXTILE COMPOSITES

John E. Masters
Lockheed Engineering and Science
Hampton, VA

Peter G. Ifju
Virginia Polytechnic Institute
Blacksburg, VA

Mark J. Fedro
Boeing Defense and Space Group
Philadelphia, PA

INTRODUCTION

NASA's Advanced Composite Technology (ACT) Program was initiated in 1990 with the purpose of developing less costly composite aircraft structures. A number of innovative materials and processes have been evaluated as a part of this effort. Chief among them are composite materials reinforced with textile preforms.

These new forms of composite materials bring with them potential testing problems. Methods currently in practice were developed over the years for composite materials made from prepreg tape or simple 2-D woven fabrics. A wide variety of 2-D and 3-D braided, woven, stitched, and knit preforms have been suggested for application in the ACT program. The applicability of existing test methods to the wide range of emerging materials bears investigation. The overriding concern is that the values measured are accurate representations of the true material response.

The ultimate objective of this work is to establish a set of test methods to evaluate the textile composites developed for the ACT Program.

OUTLINE OF PRESENTATION

The figures contained in this paper reflect the presentation made at the conference. They may be divided into four sections as the outline listed below illustrates. A definition of the problem serves as the introduction to the paper. This is contained in the next three figures which outline the methods being investigated and summarize items of concern in applying them to textile composites. This section will be followed by a review of results obtained in a related study of 2-D triaxially braided textile composite materials. These results illustrate the concerns outlined in the introduction. A description of the on-going test methods development effort will be reviewed in the third section. This program, which is in its initial stages, involves a number of investigators in government, universities, and the aircraft industry. The approach taken in the program will be defined. This will be accompanied by an inventory of the material systems being investigated and a list of test methods and investigators. Finally, a short summary will conclude the paper.

- **INTRODUCTION**
  - **Mechanical Tests Applied to Current Materials**
  - **Statement of Problem**
  - **Textile Composite Concerns**
- **2-D BRAID TEST RESULTS**
  - **Material Description**
  - **Moiré Interferometry**
  - **Strength and Modulus Measurements**
- **ON-GOING TEST METHODS DEVELOPMENT EFFORT**
- **SUMMARY**

STATEMENT OF PROBLEM

The problem to be addressed is summarized in the two bullet statements given below. Simply stated, the test methods listed in the previous figure were developed to evaluate composite materials formed by laminating layers of pre-impregnated fiber-reinforced tape. The microstructure of these laminated composite materials differs significantly from the braided, woven, and stitched materials to be evaluated in this program. The fiber architecture will play a prime roll in determining the mechanical response of these textile composite materials. Will existing methods and practices accurately reflect the material response of these materials?

- **TEST METHODS DEVELOPED FOR LAMINATED TAPE COMPOSITES**

- **TEXTILE ARCHITECTURE CONTROLS MATERIAL RESPONSE**

SCREENING AND CHARACTERIZATION TESTS APPLIED TO LAMINATED TAPE COMPOSITES

The first step taken to meet the program objective was to survey the aircraft manufacturers who were active participants in the ACT program. All organizations were asked to identify the mechanical and physical properties they typically measured to evaluate a new material system. Their response formed the basis for efforts to develop test methods for composite materials reinforced with textile preforms.

Six organizations responded to the inquiry. Each has its own distinct identity and design philosophy. Their approaches to evaluating new materials, however, had many common elements.

The common theme that emerges is that testing of a new material system is conducted in three stages: material screening, material characterization, and development of design allowables. Although none of the test matrices were identical, a number of the tests were common to all lists. The practices employed by the manufacturers in the screening and characterization phases of investigation are listed below in the figure.

TEST TYPE	TEST METHOD
• TENSION:	
Unnotched	ASTM D3039, D3518 MISC. COMPANY METHODS
Notched	SACMA SRM 5 NASA 1142- B9
• COMPRESSION:	
Unnotched	ASTM 3410 SACMA SRM1 NASA SHORT BLOCK MISC. COMPANY METHODS
Notched	SACMA SRM 3 NASA 1092 ST-4 MISC. COMPANY METHODS
• COMPRESSION AFTER IMPACT	SACMA SRM 2 NASA 1142 B11
• BOLT BEARING	MISC. COMPANY METHODS
• INTERLAMINAR TENSION	FLATWISE TENSION CURVED BEAM
• INTERLAMINAR SHEAR	ASTM D2344
• MODE I DELAMINATION	DOUBLE CANTILEVER BEAM
• MODE II DELAMINATION	END NOTCHED FLEXURE

TEXTILE COMPOSITE TESTING ISSUES

It is not difficult to identify a number of specific testing issues relative to textile composites. Several of these concerns, which are applicable to virtually all of the test methods listed on the previous page are listed below.

The first two reflect the unique size effects these materials may present. A unit cell is defined as the smallest unit of repeated fiber architecture. It may be considered the building block of the material. The size of the unit cell is dependent on a number of factors including the size of the yarns, the angle at which they are intertwined or interwoven, and the intricacy of the braid or weave pattern. A representative volume of material must be tested and monitored to accurately reflect true material response. Specimen geometry and strain gage sizes must be reexamined in terms of unit cell size. The effect of the sizes of the yarn bundles must also be considered since they may also effect the performance and the measurements. This is expressed in the third statement.

The final three items on the list reflect concerns over specimen geometry. Test specimen dimensions established for tape type composites may not be applicable to textile composites. The degree of heterogeneity present in the latter materials is quite different than that encountered in the former. The potential effects of these differences must be also quantified.

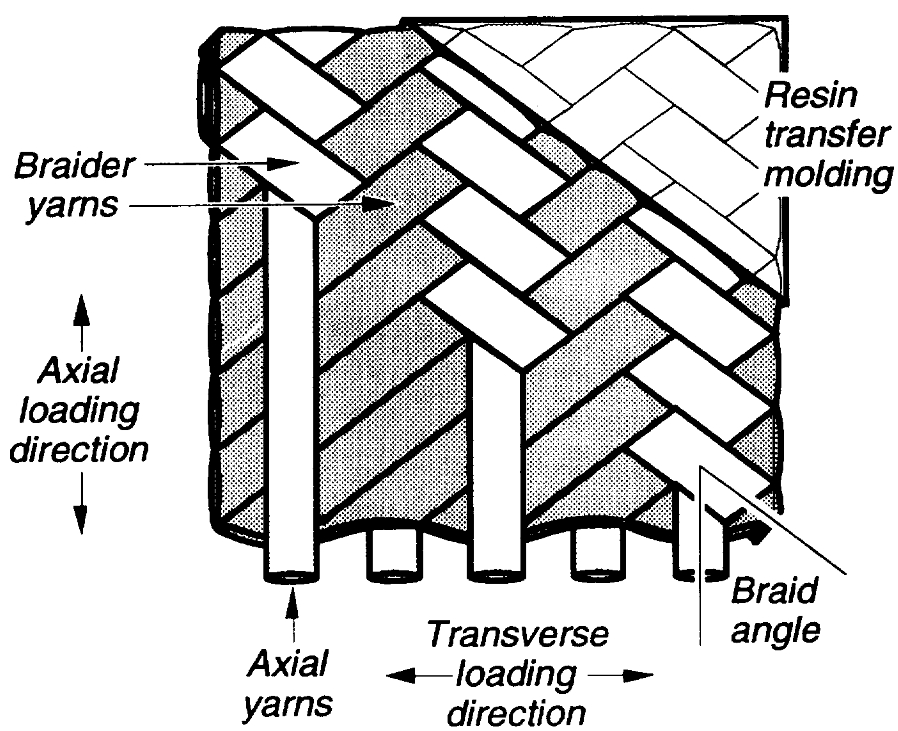
A limited amount of relevant data has been developed for 2-D triaxially braided textile composites. These results will be reviewed in the following section. They include Moiré interferometry and strength and modulus measurements.

- **EFFECT OF UNIT CELL SIZE ON MECHANICAL PERFORMANCE**
- **EFFECT OF UNIT CELL SIZE ON STRAIN GAGE AND DISPLACEMENT MEASUREMENTS**
- **EFFECT OF TOW SIZE AND FIBER ARCHITECTURE ON MECHANICAL PERFORMANCE**
- **EFFECT OF FINITE WIDTH ON UNNOTCHED AND OPEN-HOLE SPECIMENS**
- **EFFECT OF EDGE CONDITIONS ON MECHANICAL PERFORMANCE**
- **EFFECT OF TEXTILE THICKNESS ON MECHANICAL PERFORMANCE**

TRIAXIAL BRAID PATTERN:
DESCRIPTION OF MATERIAL TESTED

The specimens studied in this investigation featured 2-D triaxially braided AS4 graphite fiber preforms impregnated with Shell 1895 epoxy resin. In a triaxially braided preform three yarns are intertwined to form a single layer of $0^\circ/\pm\Theta^\circ$ material. In this case, the braided yarns are intertwined in a 2 x 2 pattern. Each $+\Theta$ yarn crosses alternatively over and under two $-\Theta$ yarns and vice versa. The 0° yarns were inserted between the braided yarns. This yields a two dimensional material. The figure below schematically illustrates the fiber architecture and establishes the nomenclature used in the paper.

The yarns were braided over a cylindrical mandrel to a nominal thickness of 0.125 in. The desired preform thickness was achieved by overbraiding layers; there are no through-the-thickness fibers. After braiding, the preforms were removed from the mandrel, slit along the 0° fiber direction, flattened, and border stitched to minimize fiber shifting. The resin was introduced via a resin transfer molding process.



Three preform parameters, braid angle, yarn size, and 0° yarn content, were varied in this study. The last parameter listed is typically expressed as a percentage of 0° yarns. It is the volumetric proportion of longitudinal yarns to total yarn content and is a function of braid angle and yarn size. Yarn size is expressed in terms of the number of filaments per yarn. The AS4 fibers used in these materials have a nominal diameter of 7 microns. The longitudinal yarns were larger than the braided yarns in all cases. The B1 and B2 architectures had the same yarn sizes; they differed in braid angle and 0° yarn content. The preform parameters are listed in the table.

The fabrics were formed with a 144 carrier New England Butt triaxial braider, incorporating 72 longitudinal yarns. The mandrel diameters varied for each architecture. Since the number of carriers was constant, this had the effect of changing the yarn spacing. These parameters are also listed in the table.

MATERIAL	BRAID PATTERN	BRAIDER YARN SIZE	0° YARN SIZE	0° YARN CONTENT (%)	0° YARN SPACING (Yarn/In.)	BRAID YARN SPACING (Yarn/In.)
A1	0/± 63°	12K	24K	31.5	4.17	9.16
B1	0/±66.5°	6K	18K	37.6	4.77	11.98
B2	0/±70°	6K	18K	34.0	4.37	12.74

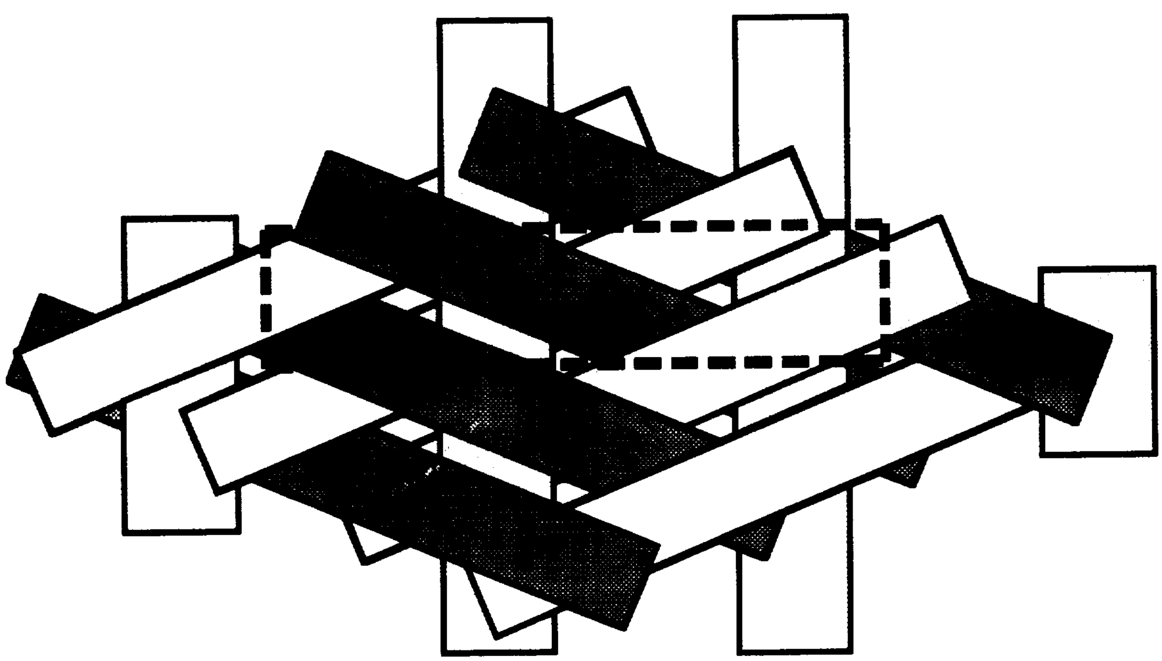
Note: K indicates thousands. For the AS-4 yarns, each filament is 7 microns in diameter

UNIT CELL DEFINITION

A convenient way to describe textile preforms is to identify a unit cell of material - a repeatable unit of fabric geometry. The unit cell represents the complete yarn intertwinement pattern. The unit cell approach has become the foundation of textile analysis and serves as a convenient framework in which to interpret experimental data.

The rhombic frame shown in the figure defines a unit cell for the 2-D triaxially braided material studied in this program. For computational purposes, it is desirable to define the smallest unit cell possible. In some analyses, rectangular unit cells are also required. The rectangular section shown in the figure represents the smallest unit cell identified.

The table shown below contains the dimensions of the unit cells for the three architectures tested. The unit cell width is dependent on the mandrel diameter and the number of yarns braided. The height of the unit cell is dependent on the cell width and the braid angle. Even though a conservative definition of the unit cell was applied in this case, the data in the table indicate that the unit cells can be quite large compared to typical specimen and strain gage dimensions.



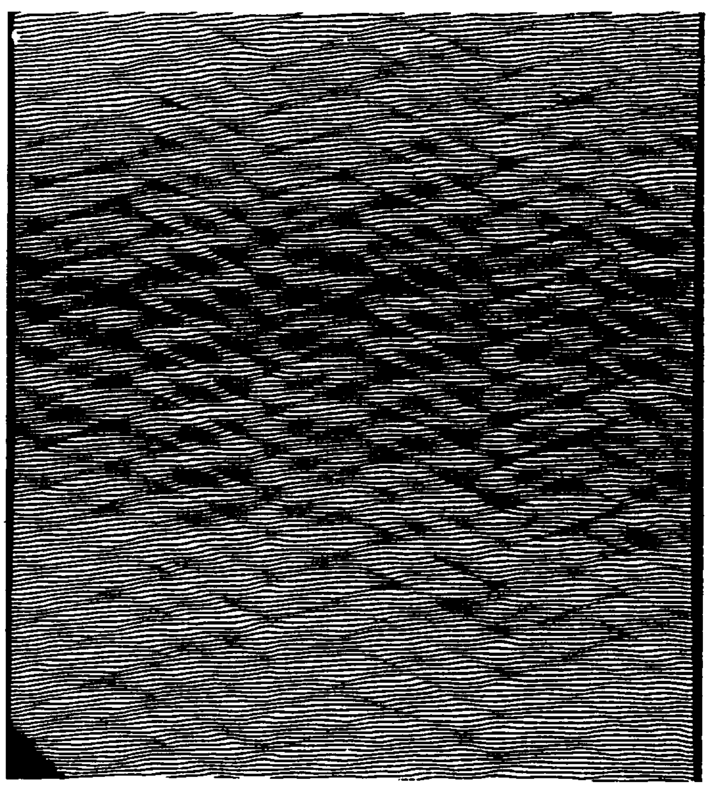
UNIT CELL DIMENSIONS

MATERIAL	WIDTH (in.)	HEIGHT (in.)
A1	0.48	0.12
B1	0.42	0.09
B2	0.46	0.08

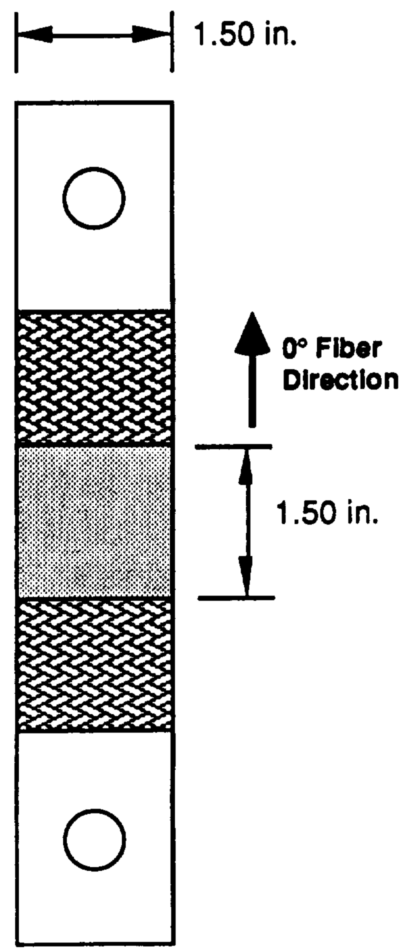
As indicated earlier, Moiré interferometry was used to define the full field strain distribution in these braided specimens. The technique defines deformation patterns in both the vertical and horizontal directions. The technique was applied to specimens subjected to longitudinal and transverse loading. These results are shown in this and the following figures.

The figure below illustrates the specimen geometry and highlights the section studied. The vertical displacement field that resulted when a specimen was loaded to 1200 micro-strain along the 0° fiber direction is also shown in the figure.

The vertical displacement fields (V fields) consist of basically horizontal fringes; this indicates specimen extension where points along one fringe have been displaced vertically with respect to points along a neighboring fringe. For a uniform extension the fringes should be evenly spaced and straight. The fringes for the specimens tested, however, are wavy and the spacing between them varies. The variation is cyclic and coincides with the repeated unit of the textile architecture.

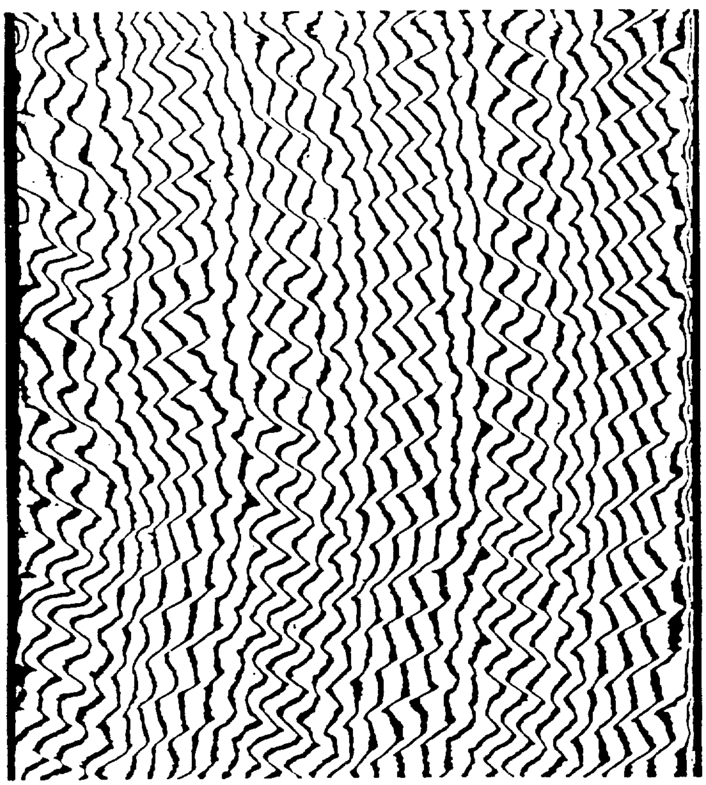


Vertical Displacement Field

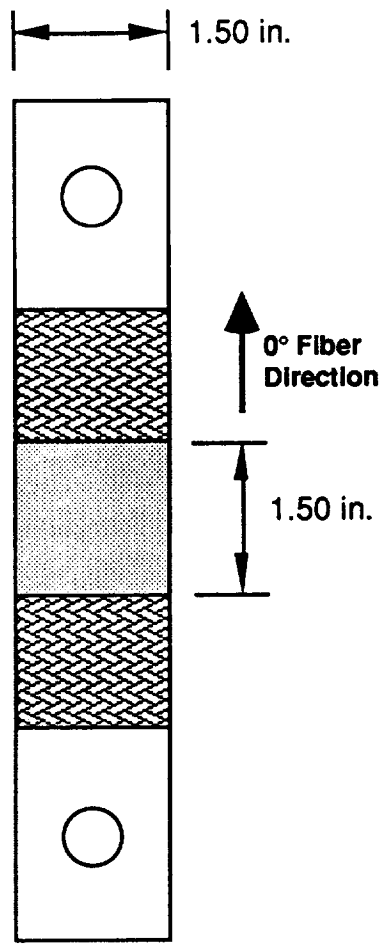


MOIRÉ INTERFEROMETRY
Axial Load - Horizontal Displacement Field

The horizontal displacement patterns (U fields) consist of zigzag vertical fringes that display the Poisson's effect. For uniform contraction the fringes should be straight and the spacing constant. The fringes however display a variation which is cyclic, and matches that of the braid geometry. The sharp kinks in the U field fringes reveal the presence of shear strains between the fiber bundles.

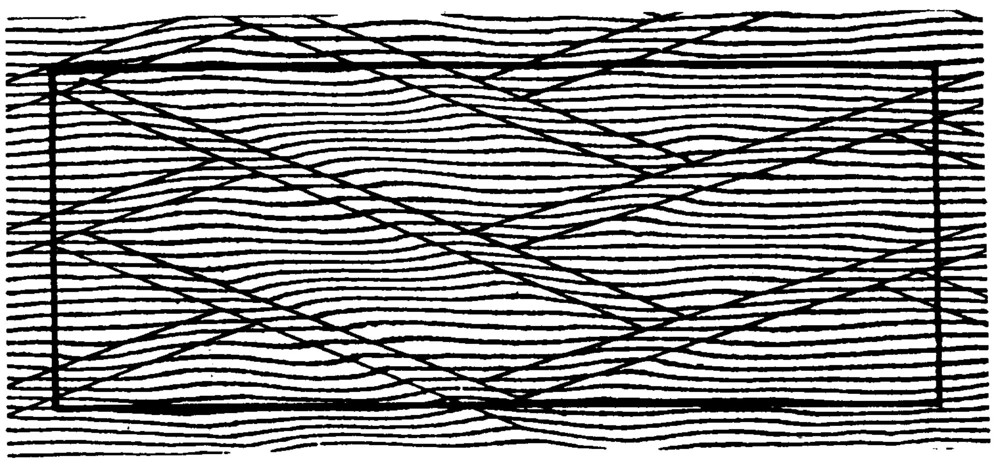


Horizontal Displacement Field

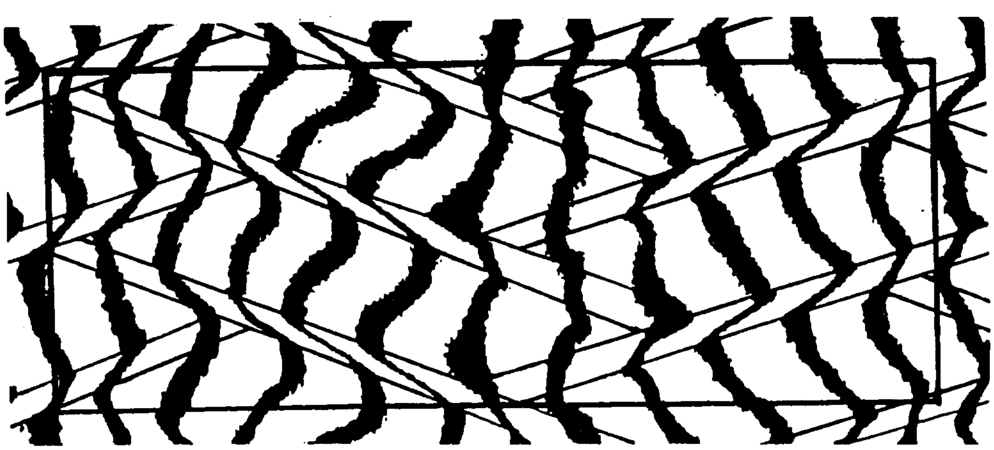


ENLARGED VIEW OF TWO UNIT CELLS OF SPECIMEN
(Axial Loading)

The figure shows the V and U fields of a highly magnified region of specimen that consists of two unit cells. The boundaries between adjacent fiber bundles and the outline of the cells are marked. It was revealed that the shear deformation at interfaces between the fiber bundles occurred over a finite width. This width is illustrated in the patterns as the distance between the closely spaced lines. This is consistent with the presence of the resin rich areas between the fiber bundles, which was on the order of one fifth of the width of the fiber bundle itself. The U field shows that the shear strain γ_{xy} in the resin rich zones was on the order of 0.5 times that of the average applied normal strain ε_y. Additionally, the U field shows that the Poisson effect was nearly constant across the unit cell. The V displacement pattern clearly shows that the strain ε_y varies significantly within each unit cell as can be seen by the nonuniform fringe spacing. The ratio of maximum strain ε_y to minimum strain was about 2 to 1. The normal strain varies on top of the fiber bundles and is nearly constant throughout all of the resin rich zones.



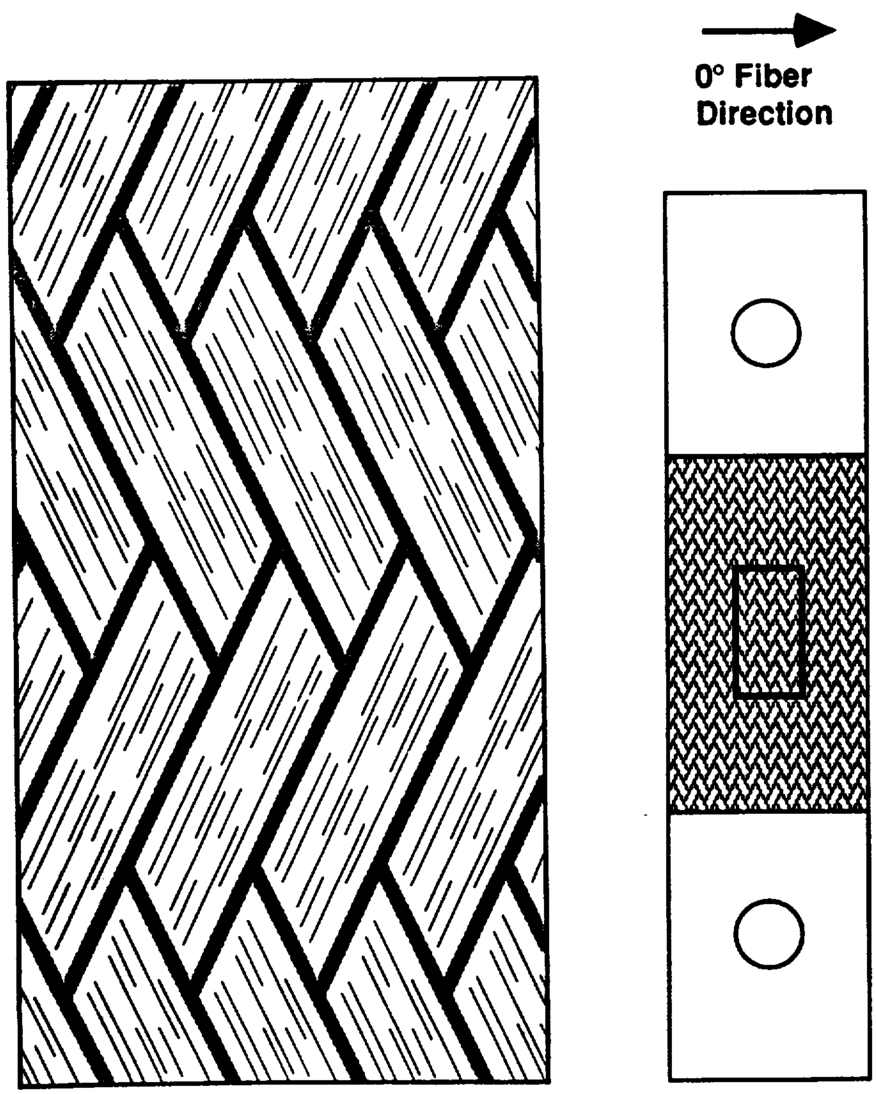
Vertical Displacement Field



Horizontal Displacement Field

SPECIMEN SECTION COINCIDING WITH MOIRÉ FRINGE PATTERNS (Transverse Loading)

Interferometry was also performed on specimens loaded in the transverse direction (i.e. at 90° to the axial direction). This figure shows the region investigated in these specimens. The pattern of the surface braided yarns is shown schematically in the figure. The deformation fields that developed in these coupons are shown in the next two figures.

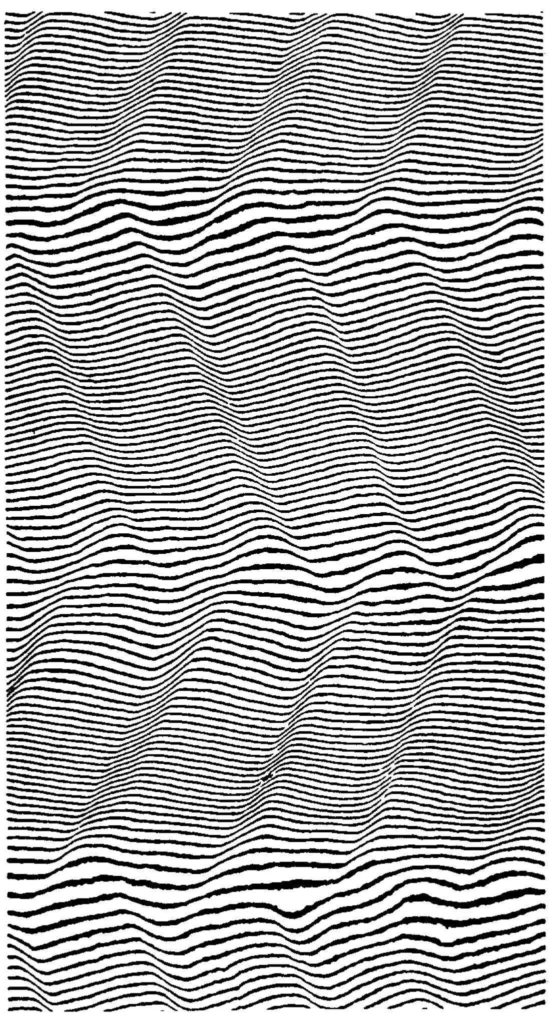


MOIRÉ INTERFEROMETRY
Transverse Load - Vertical Displacement Field

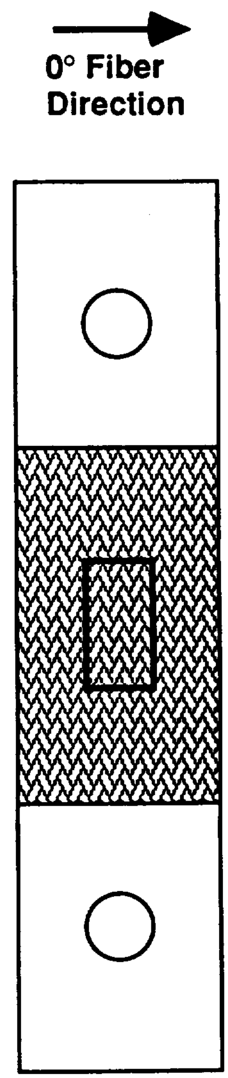
In general, the interferometry results indicate that greater variations in normal and shear strains existed in specimens loaded in the transverse direction than in the axial direction.

This figure displays the vertical displacement field for a coupon loaded in the transverse direction. The location of the yarns are evident in the vertical displacement fringe patterns, where sudden jogs in the fringes represent strong shear strains in the resin rich regions between the yarns. From the V displacement pattern, the spacing of the fringes in the vertical direction displays a cyclic variation. The strains are highest over the region where there are 90° fibers under the braider yarns. They are lowest over the regions where the braider yarns cross. The difference between the average strains in these areas is on the order of 3 times.

Unlike the axial loading case, the cyclic variation is not confined to the dimensions of the unit cell. The variation breaches the unit cell to form a global material response that covers the entire specimen. This is illustrated by the horizontal bands seen in the figure. They span several unit cells and extend across the specimen width.



Vertical Displacement Field

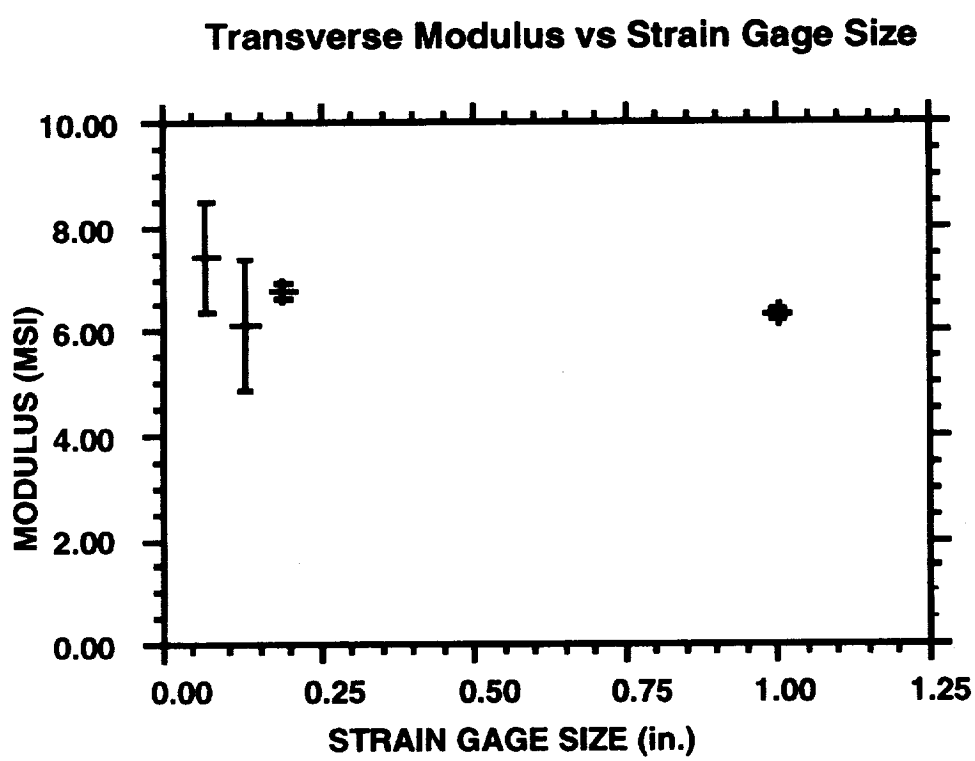


CONSIDER STRAIN FIELD INHOMOGENEITY WHEN CHOOSING INSTRUMENTATION

The inhomogeneity in the strain fields demonstrated in the Moiré interferometric results discussed in the previous slides has significant implications with regard to specimen instrumentation. The large strain gradients seen within the unit cell graphically illustrate the need to measure strain over a truly representative volume of material to get an accurate determination of the global material response. Local strain readings can be misleading and confusing.

The data shown in the figure below demonstrate these points. The figure plots the measured transverse modulus of several B1 laminates vs. the size of the gages used to measure the strain. The gages ranged in length from 0.062 in. to 1.0 in.; the preform's unit cell measures 0.42 in. in this direction. The average modulus and the standard deviation of the data are shown in the figure. As the figure indicates, significant scatter was evident in the results obtained using the small gages. These effects were reduced as the length of the gage increased. The results also indicate that average value also decreased as strain gage size increased.

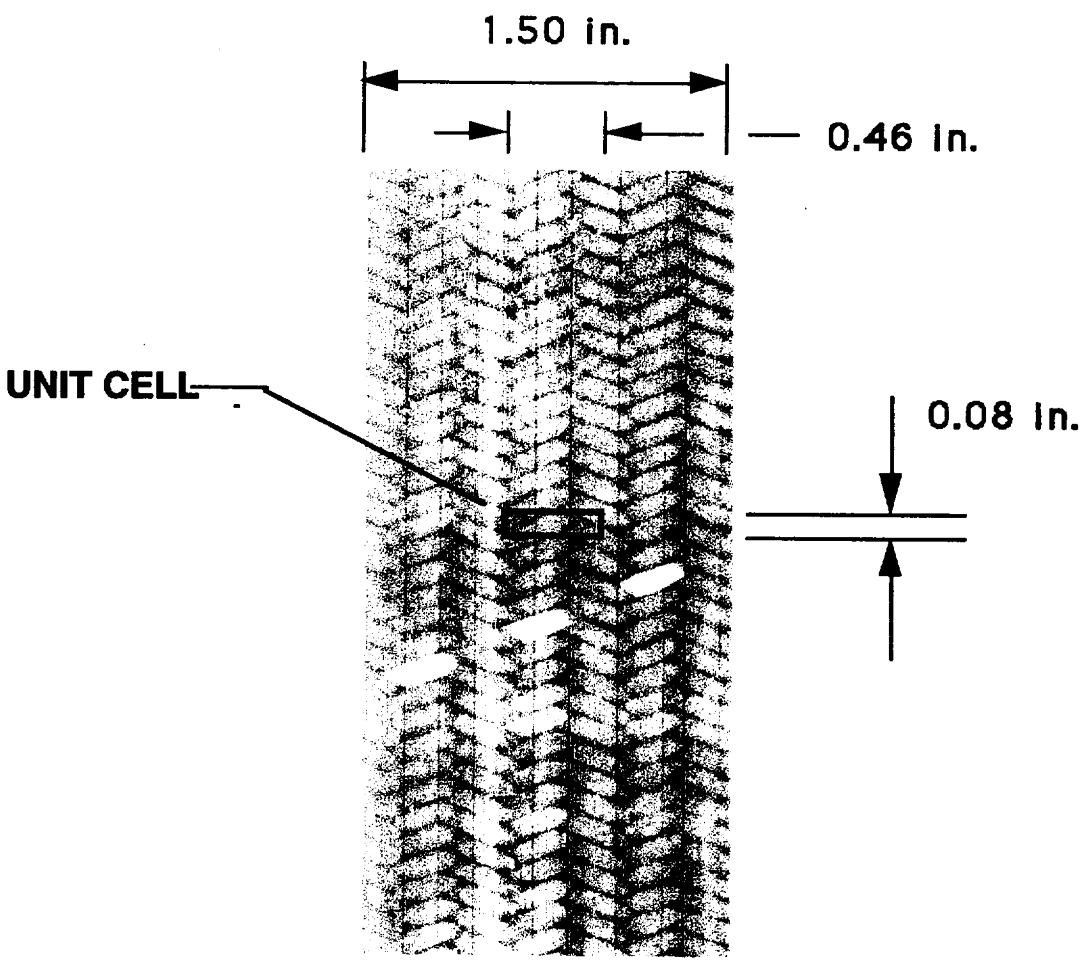
The results illustrate the need to consider the textile architecture when choosing instrumentation for a specimen.



MATERIAL ARCHITECTURE AND TEST COUPON GEOMETRY

The preform architecture must also be considered when designing test specimens. The figure below contains a photograph of a tensile test coupon. The specimen, which is typical of those commonly used in screening and evaluation test programs, is 1.5 in. wide and 10 in. long. Superposed on the photograph are the B2 architecture's unit cell dimensions. As the figure illustrates, when oriented in this direction, the specimen is only three unit cells wide. This again raises the question of whether a representative volume of material is being sampled in the test.

Specimen width and thickness must be considered when designing test specimens to attain true measures of modulus and strength. Unfortunately, design criteria have not yet been established for these materials.

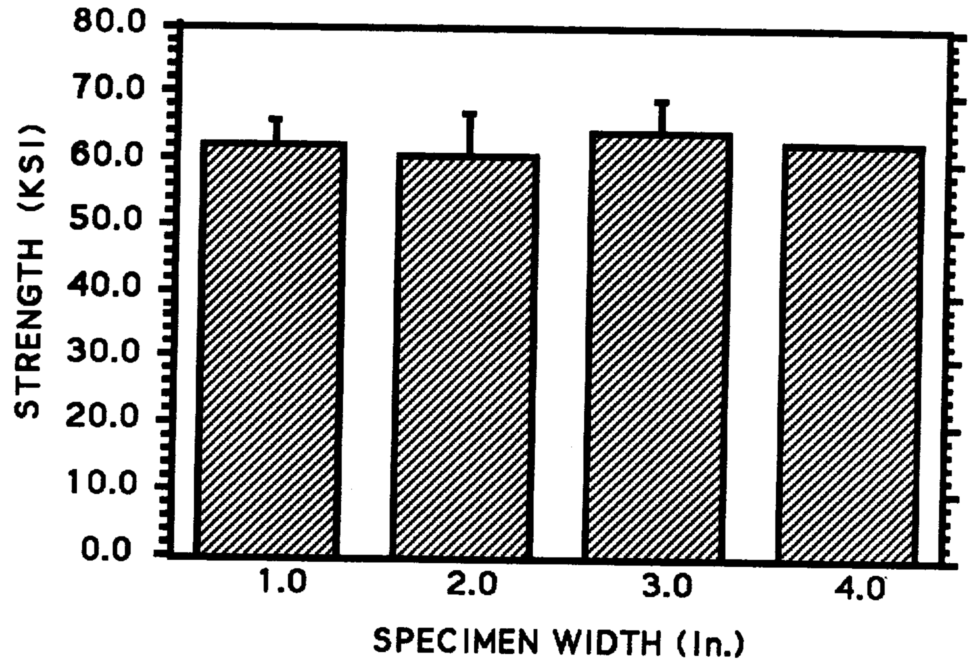


EFFECT OF SPECIMEN WIDTH ON STRENGTH
(Data Normalized to 55% Fiber Volume)

A series of longitudinal tensile tests were conducted to judge cursorily the effect of specimen width on strength of the B2 type 2-D triaxially braided laminates defined in an earlier figure. In these tests specimen width was varied from 1.0 in. (2 unit cells wide to 4.0 in. (8 unit cells wide).

The results of these tests are shown in the figure below. The data, which have been normalized to 55% fiber volume to simplify the comparison, indicate that specimen width had no apparent effect on the test results for this architecture. The average strengths and the standard deviations of the results (indicated by the bars in the figure) were comparable for each group of tests (note: the 4.0 in. data represents the average of two tests; the standard deviation was not computed).

A larger, more complete examination of the interaction of textile architecture and test laminate geometry is underway as a part of an effort to develop test methods for textile composites. This effort will be outlined in the following pages.



TEST METHODS DEVELOPMENT: PROGRAM OBJECTIVE

As indicated below, the objective of this on-going effort, simply stated, is to develop a set of test methods and guidelines to be used to measure the mechanical and physical properties of composite materials reinforced with fibrous textile preforms. Investigations conducted to date have indicated that existing methods, which were developed largely to evaluate laminated tape type composites, may not adequately address the subtleties of these new material forms.

DEVELOP AND VERIFY NASA RECOMMENDED MECHANICAL TEST PROCEDURES AND INSTRUMENTATION TECHNIQUES FOR TEXTILE COMPOSITES

TEST METHODS DEVELOPMENT: PROGRAM APPROACH

A straightforward approach has been adopted to meet the objective outlined in the previous figure. An extensive test program will be conducted to gather data addressing the concerns listed earlier. The program, which will include a wide variety of woven, braided, and stitched preform architectures, will consider several loading conditions.

The general approach is outlined in the figure below. Details of material tested and test methods are supplied in the following pages.

- **IDENTIFY AND/OR DESIGN AND DEVELOP SPECIMEN CONFIGURATIONS AND TEXT FIXTURES**

- **CONDUCT MECHANICAL TEST PROGRAM**
  - **Variety of Test Methods**
  - **Variety of Instrumentation Techniques**
  - **Full Field Strain Measurements**
  - **Analytical Support**

- **IDENTIFY SMALLEST LEVEL OF HOMOGENEITY**

- **IDENTIFY APPROPRIATE TEST METHODS AND INSTRUMENTATION GUIDELINES**

MATERIAL SYSTEMS FOR TEST METHOD DEVELOPMENT

Fifteen woven, braided, and stitched preforms will be evaluated in the program. The preform types are listed below in the table; the number of each type to be tested is indicated in parentheses. The table also lists the braid parameter that will be varied for each preform type. The list of materials reflects the material forms that are being evaluated by the aircraft manufacturers in the ACT program.

TEXTILE PREFORM TYPES:

- **2-D TRIAXIAL BRAIDS - (4)**
  - Tow Size
  - % Longitudinal Tows
  - Braid Angle
- **3-D INTERLOCK WEAVE - (6)**
  - Weave Type - (3)
  - Warp, Weft, and Weaver Tow Size
- **STITCHED UNIWEAVE - (5)**
  - Stitch Material
  - Stitch Spacing
  - Stitch Yarn Size

MATERIALS:

FIBER: HERCULES AS4

RESIN: SHELL 1895

STANDARD TEST METHOD PROGRAM
FOR TEXTILE COMPOSITES

The types of tests being developed and the organizations involved in their development are listed in the table below.

TEST TYPE	ORGANIZATION
• STRAIN GAGE GUIDELINES	BOEING DEFENSE & SPACE LOCKHEED ENG. & SCIENCE
• TENSION Unnotched Notched	BOEING DEFENSE & SPACE
• COMPRESSION Unnotched Notched	BOEING DEFENSE & SPACE NASA/LANGLEY
• IN-PLANE SHEAR	BOEING DEFENSE & SPACE VA. TECH
• BOLT BEARING	BOEING DEFENSE & SPACE
• COMPRESSION AFTER IMPACT	NASA LOCKHEED ENG. & SCIENCE
• OUT-OF PLANE LOADS	NASA UNIVERSITY OF DELAWARE

SUMMARY

A brief summary of the technical results reviewed in the presentation is given below. The experimental investigation conducted on 2-D braided materials indicated that significant strain gradients existed within the materials unit cell as a result of the braid architecture. This inhomogeneity in the strain field is an important factor that must be considered when choosing instrumentation for a test specimen. Although the 2-D braided laminates tested did not demonstrate a width effect, the size of the unit cell must also be considered when designing a test specimen.

Finally, the concerns discussed above and others listed in an earlier figure will be addressed in an on-going test method development effort.

- **MOIRÉ INTERFEROMETRY IDENTIFIED LARGE STRAIN GRADIENTS WITHIN THE UNIT CELL**
- **INHOMOGENEITY IN STRAIN FIELD EFFECTS INSTRUMENTATION**
- **UNIT CELL SIZE MAY AFFECT TEST RESULTS**
- **ON-GOING INVESTIGATION TO DEFINE TEXTILE TEST METHODS UNDERWAY**