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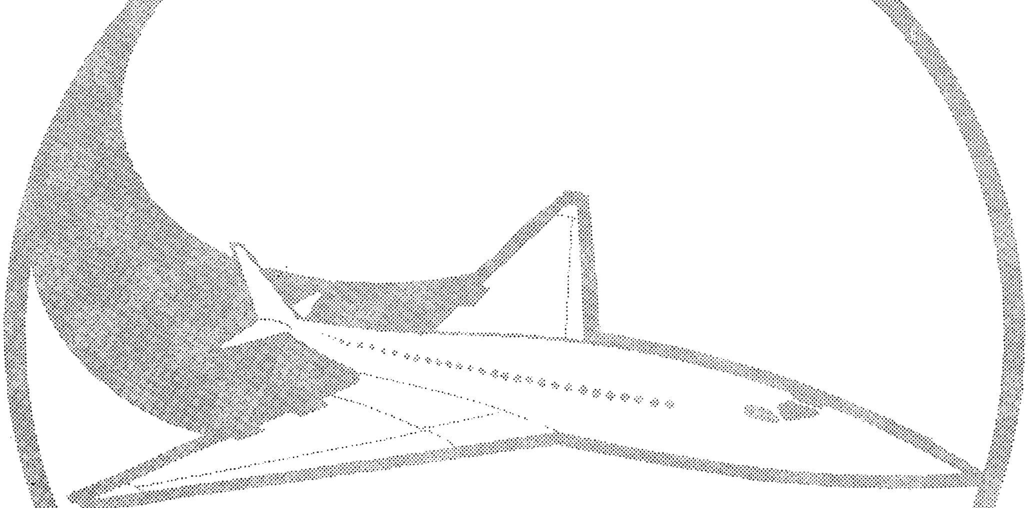
Test Methods for Composites a Status Report

Volume III. Shear Test Methods



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16. Abstract

This document provides an evaluation of current test methods for shear properties of composite materials consisting of high modules, high strength fibers in organic matrix materials. Mechanical testing is an important step in the "building block" approach to design of composite aircraft structures. The document provides a source of information by which the current shear test methods can be evaluated and from which test methods which appear to give good-quality test data can be selected. Problems with the available shear test methods are also addressed as a means of providing recommendations for future research.

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PREFACE

This document is Volume III of three volumes which have been developed to provide an assessment of mechanical property test methods for organic matrix composite materials. The present volume presents a review and evaluation of test methods for shear properties of fiber reinforced composite materials. Two companion documents, Volume I on Tension Test Methods and Volume II on Compression Test Methods, have also been prepared.

This document was developed under an Interagency Agreement between the Federal Aviation Administration Technical Center, Atlantic City International Airport, NJ and the U.S. Army Research Laboratory Materials Directorate, Watertown MA. Technical Direction was provided by D. W. Oplinger of the Federal Aviation Administration Technical Center with the advice of J. Soderquist, FAA Headquarters, Washington DC, while administrative support was provided by R. Pasternak of the Army Research Laboratory Materials Directorate. The work was performed under contract to Materials Sciences Corporation and the Composite Materials Research Group, University of Wyoming. Principal Investigator was Dr. S. Chaterjee of Materials Sciences Corporation with direction of the University of Wyoming effort by Prof. D. Adams.

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EXECUTIVE SUMMARY

This document, which constitutes Volume 3 of a three volume set, provides an evaluation of current test methods for shear properties of "advanced" composites constructed of high modulus, high strength fibers embedded in organic matrix materials such as epoxies. Mechanical testing for various structural properties is one of several essential steps in the design of composite aircraft structures. Companion volumes addressing: Tension Testing (Volume 1) and; Compression Testing (Volume 2) of composite materials, are also available. The intention is to provide a comprehensive source of information by which the current test methods for these types of property tests can be evaluated and from which test methods which appear to give good-quality test data can be selected.

The document provides: (1) a comprehensive review of performance features, advantages and negative aspects of various test methods which have been introduced for obtaining shear properties of composite materials; (2) an extensive annotated bibliography covering most documented test method development activity which has taken place since the introduction of advanced composites in the mid 1960's; (3) a ranking of the commonly used test method for shear properties, and: (4) an assessment of problem areas that continue to exist in the available test methods.

Two types of shear test were evaluated in the survey, in-plane shear which relates to general structural behavior in an aircraft component, and interlaminar, or transverse, shear which relates to behavior at joints and other design details. Results of the survey are as follows:

INPLANE SHEAR

(i) Initial shear modulus can be determined using most of the test methods, provided appropriate correction factors are used to determine shear stress in the test section based on adequate stress analysis.

(ii) A number of test methods are available which give satisfactory results for in-plane shear measurement of composites. The most popular because of its ease of use is ASTM D3518 which involves tension loading of $\pm 45^{\circ}$ forms of the material to be tested.

Although there are minor deficiencies recognized in this test because of a non-pure shear stress state, industry generally considers the test to be adequate for structural qualification of composites. More theoretically correct results are provided by several other tests which include rail shear tests (ASTM Guide D4255), picture frame shear tests and the recently adopted ASTM D5379 Iosepescu test which involves shear loading of a notched specimen; these tests are somewhat more complicated and difficult to conduct than the $\pm 45°$ tension test and for practical reasons may not be in as general use.

(iii) The most nearly ideal test from a theoretical standpoint involves torsion of thin walled filament wound tubes, currently under development as an ASTM standard. The test is difficult to conduct properly, however, and may not be representative of flat laminates processed by approaches representative of that type of material. Other torsion tests which have been studied include torsion of solid rectangular columns and circular rods. These perform reasonably satisfactorily and are convenient to apply to some forms of composites.

(iv) One type of test, ASTM D3846, involving slots cut on opposite sides of column loaded specimens, is particularly undesirable for obtaining mechanical property data. Extremely high stress concentrations induced by the slots which have a crack-like behavior render the test results more-or-less meaningless from the standpoint of the stress condition causing failure.

(v) A number of other tests which are in various stages of adequacy are discussed in the body of the report.

(vi) Ply cracks and other forms of subcritical damage, which result in nonlinear stress strain response of unidirectional composites, usually grow at differing rates which depend on the fiber orientation or lay up (0°, 90° or cross ply 0/90°) as well as the test method. For example, the off-axis tension test (tension in a unidirectional laminate oriented at an angle to the load direction) often yields very low ultimate stress and strain for common brittle epoxy systems. The use of cross ply lay up in torsion tube, Iosipescu or rail shear tests results in slow constrained damage growth (increasing number of ply cracks with increasing load) which is considered by many workers as the pattern expected in application laminates. Similar behavior is also expected in 90° rail shear and thick (>32 ply) $\pm 45°$ tension test specimens. Thinner $\pm 45°$ tension specimens yield low ultimate stresses and strains in common graphite-epoxy composites. Additional studies are suggested to address these issues.

(vii) Simple modifications to some of the methods may yield better specimen performance. For example, redesigning the grip regions in solid torsion specimens appears worthwhile. On the other hand, significant modifications may be required in some other methods such as picture frame or crossbeam.

INTERLAMINAR SHEAR

(i) Iosipescu tests with specimens prepared by bonding several layers of a material appear to be the only available method at this time for determining interlaminar stress strain response. Obviously specimen preparation needs some effort and the quality of the bond may affect the results in some cases.

(ii) short beam shear is one of the simplest test to conduct and it is often used, but test data are usually not accepted as material shear properties, since failure can be influenced by flexural and contact stresses. Further studies are suggested for three and four-point loaded short beam as well as lap shear tests used for measuring shear strengths.

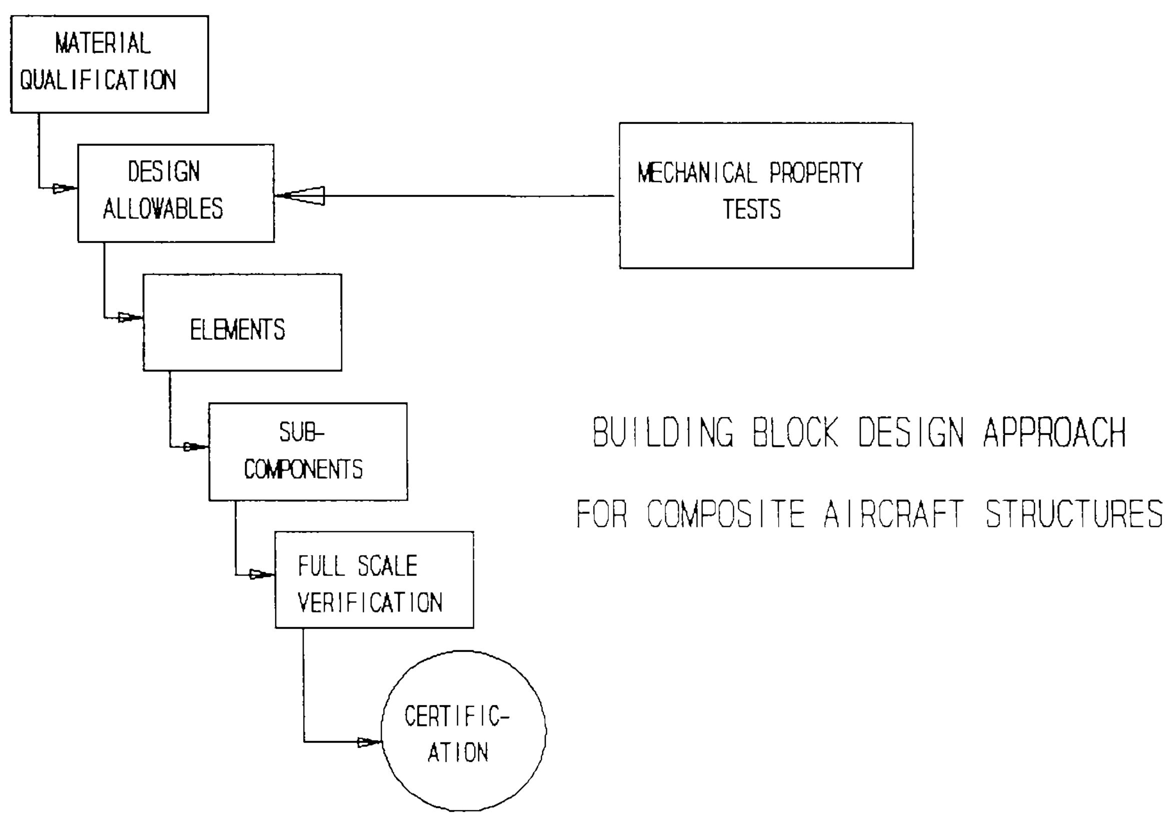
(iii) the slotted or notched shear test is possibly most economical, and for this reason it is often used for quality control purposes, but the results are influenced by the severity of stress concentration at the notches. Because of the economy and wide usage, additional studies are suggested for possible improvements of the test and careful comparison of test data with those from other tests.

In summary, it can be noted that a few standards are either available or under development for some in plane shear test methods. Further work is suggested for improving the $\pm 45°$ tension test for in plane shear and three- or four-point loaded short beam shear test (or some other reliable method) for interlaminar shear. In the meantime, it is hoped that the discussions and suggestions contained in this report will be useful in deciding on test methods, specimens, procedures and interpretation of data.

OVERVIEW

GENERAL REMARKS

This document which constitutes Volume 3 of a three volume set, provides an evaluation of the state of the art of current test methods for obtaining shear properties of "advanced" composites constructed of high modulus, high strength fibers embedded in organic matrix materials such as epoxies. Mechanical testing is an important step in the "building block" approach to design of composite aircraft structures, as illustrated in the Figure below. Companion volumes addressing: Tension Testing (Volume 1) and; Compression Testing (Volume 2) of composite materials, are also available. The intention is to provide a source of information by which the current test methods for these types



Mechanical Property Testing in Composite Aircraft Design

of property tests can be evaluated and from which test methods which appear to give good-quality test data can be selected.

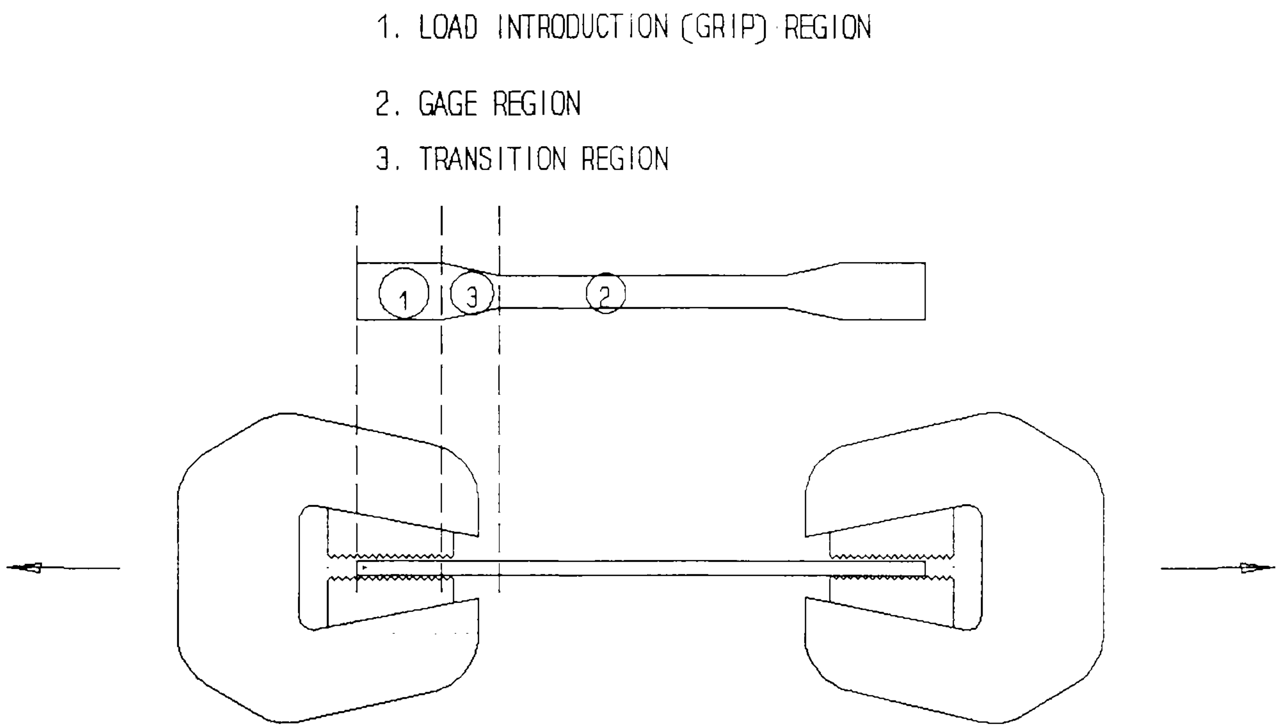
Mechanical property testing of advanced composites has been under development ever since the introduction of such materials nearly a generation ago. The first major conference on test methods for advanced composites, for example, took place in 1969 and culminated in ASTM Special Technical Publication STP 460 which summarized results from a number of DoD programs that were ongoing at that time. The methods which were reported on that occasion formed the basis for a number of test methods which are still in use.

The methodology for obtaining mechanical properties of such materials contains a number of inadequacies and is in need of continuing development. The purpose of this discussion is to review the issues which are significant drivers in efforts toward improved testing methodology, in order to provide a framework for evaluating the state of the art.

OBSERVATIONS ON MECHANICAL PROPERTY TESTING OF COMPOSITES

Mechanical property measurements in structural materials can be characterized in terms of three regions in the test specimen (illustrated in the following Figure for a generic tension test): (1) a load introduction or gripping region, where large stress peaks associated with the load introduction method are compensated for by a relatively large loaded area; (2) a central ("gage") region of relatively small loaded area where failure is meant to be produced, and; (3) a transition region joining the gage and grip regions. (A clear cut transition region, (3), is not present in many types of test specimen).

The gripping region is characterized by complex loading features, often involving very peaky stress distributions associated with hard contact points. Three dimensionality in the form of stress variations through the thickness is frequently present in the grip region. In the representative case shown on the following page, the load is introduced through the hard teeth of serrated surfaces of a wedge grip which results in through-the-thickness shearing; in the transition region this translates into spreading of the load in the lateral direction via in-plane shearing. Softening layers which may include tabs, thin sandpaper sheets or other approaches, may be present in the grip region. In beam-type specimens used for short beam shear and flexure testing, hard contact points represented by small-



Elements of Generic Test Specimen

radius rods of a relatively rigid material such as steel may be present that give rise to severe stress peaks in the load introduction region which are unrelated to the desired stress state.

The ideal mechanical property test specimen would provide a large effective loaded area in the grip region to compensate for stress peaks caused by the gripping arrangement, while allowing the stresses in the gage region to approach a uniform condition of high stress which ensures that failure takes place in that region. Furthermore, sufficient volume of test material should be involved in the gage region to provide an adequate sampling of the variability which is characteristic of the material being tested. For various reasons, such an ideal form of behavior is hardly ever achieved in practical test specimens for composite materials.

Specific problems which hamper successful mechanical property measurements in organic matrix composites will be summarized at this point.

Measurement of mechanical properties in organic-matrix composites is difficult because of a general lack of ductile response together with large differences in the mechanical strengths of such materials for stresses in various directions. The problem is relieved somewhat for materials reinforced in more than one direction because the strength differences are considerably less in such cases, but the requirements of the technology are currently set by those for unidirectionally reinforced materials.

For the situation shown in the preceding Figure, for example, a metallic specimen will be relatively insensitive to the indentations caused by the serrations of the loading grips, and no special difficulty will be caused by the details of the transition region, since local yielding will cause the stress at any cross section to tend toward a uniform "P-over-A" value (i.e. nominal stress defined by load divided by section area) applicable to the section under consideration; these "P-over A" stresses will be obliged to have their maximum values in the gage region by the mechanics of the situation, specifically the fact that the smallest section occurs there, so that satisfactory confinement of failure to the gage region will be obtained. Accordingly, there is little need for concern over the possibility of not obtaining representative failures in metallic test specimens.

In the case of organic composites reinforced with high strength/high modulus fibers, on the other hand, achievement of representative failure is difficult. For example, it was found early in the development of the technology of advanced composites that for tension and compression testing, width-wise tapering to form a stress-focussing transition region (see the preceding Figure) usually leads to splitting failures in the tapered region long before a valid failure can be obtained in the gage region. This tendency appears to be related to excessively low shear strength of organic matrix composites in comparison with their tensile or compressive strength in the fiber direction. For the case of tension testing, the problem was dealt with in early efforts by the introduction of rectangular (i.e. uniform width) test coupons with thickness-wise bonded-on doublers (i.e. tabs) at the ends, through which the load was sheared in. This is generally accepted practice for tensile testing, as well as a number of compression test specimen designs.

On the other hand, the processes governing the behavior of the tabs lead to high stress peaks at the gage ends of the tabs, so that failures near or inside the tabs are quite likely and are commonly observed. Even though a consensus developed for the use of tabs, they obviously do not achieve the type of behavior described previously as the ideal of a test specimen design. Moreover, a number of practical difficulties are associated with tabs.

Debonding of tabs is certainly not unusual, and is especially troublesome for test situations involving high temperature and humidity. In other words, the use of tabs as a supposed cure for the problem of splitting in width tapered tension and compression specimens is not a completely adequate solution. This kind of poor choice of alternatives characterizes many situations in the testing of composites.

An additional complication is caused by the fact that designers of composite structures need a much larger variety of property measurements than those working with metals. In the latter case a single yield strength based on a tension test is adequate for predicting yield-related failure in tension, compression and shear loading, due to the fact that failure modes corresponding to various loading modes in metals can be traced back to the same yield condition through the use of Mohr's circle transformations. In composites, the design can generally not proceed without independent measurements of tension, compression and in-plane shear properties, both modulus and strength, as well as a number of other properties, each of which has a unique failure mode that cannot be inferred from other loading modes.

In addition to increased effort corresponding to the requirement for a greater variety of test measurements, special difficulties specifically associated with compression testing arise. These have to do with the fact that properties often have to be measured on thin-gage specimens which tend to be prone to Euler column buckling prior to valid compression failure of the test material.

Greater variability of fibrous composites is also a factor which leads to problems in mechanical property testing. Not only are structural metals produced from extremely mature technology, but they are formed in large lots of highly homogenized constituents, and uniformity of strength and modulus is to be expected with them. Composites are built up by mechanical placement of constituent reinforcement and matrix components using methods which cannot be controlled to nearly the same level of uniformity. Reflection of this variability in mechanical property test data is a legitimate result, but variability may also be an undesirable characteristic of the test method. Lack of consistency between test results obtained on the same lot of material from different organizations is a common occurrence.

FACTORS AFFECTING PERFORMANCE OF TEST SPECIMENS

In view of the above comments, certain specific issues can be cited as a basis for judging which of the current test methods are well in hand vs. which are in need of additional development effort. These include: (1) whether or not the test produces a valid failure mode; (2) whether the stress distribution in the specimen is such as to insure failure in the gage region as opposed to the development of spurious failures; (3) sensitivity of the test results to practical considerations such as specimen machining tolerances, specimen surface finish requirements and accuracy of alignment of the specimen in the test machine.

These issues are clarified in the following discussion.

Failure Modes for Various Types of Loading

Except for buckling in the case of compression specimens, spurious failures are usually the consequence of severe stress concentrations in the load introduction region. Some obvious examples can be stated.

Tabbed specimens tend to fail in many cases at the tab ends or inside the tabs. Stress analysis shows that stress peaks which occur there are unacceptably severe unless the tab ends are bevelled at angles as low as 10°. Failures in the tab bonds can be expected at high temperature and humidity because of the limitations of typical adhesives. Such failures may be less likely in compression testing because of the compressive nature of transverse extensional stress to which bond materials tend to be sensitive.

Many types of compression specimen are subjected to column buckling failure because of the need for thinness in the specimen. End loaded compression specimens often fail by "brooming", i.e. splitting apart of fibers near the loading platens. It is not clear that the mechanism of brooming is adequately understood.

Width tapered specimen shapes tend to fail prematurely because of shear stresses associated with the tapered portion. With cross-plied materials, however, width-wise tapering is somewhat more successful because the spurious stresses associated with tapering tend to be relatively lower and because the cross reinforcement tends to strengthen the material against undesirable failures.

Beam-type specimens (flexure and short beam shear tests) tend to fail prematurely due to contact stresses near loading points which are non-representative of desired failure modes.

Status of Stress Analysis in Test Specimens

Stress analysis has been carried out for some width tapered specimens, which show that linearly tapered ("bowtie") shapes, as well as so-called "streamline" shapes give better performance that "dogbone" shapes such as the ASTM D638 specimen which was originally developed for plastics but has often been used for testing of composites. Comparison of analytical and experimental results have confirmed that the D638 is prone to failures at the end of the tapered region where the stresses are maximum.

Stress analyses of tabbed specimens have shown that severe stress peaks occur at the ends of the tabs, and that the use of bevelled ends on the tabs is probably not effective for tab angles greater than 10°. Linear elastic analyses of the effects of tab material indicate large differences in peak stresses for steel tabs vs. fiber glass tabs which are not necessarily reflected in test results. Ductility of the adhesive used to bond tabs, which probably has not been investigated analytically to date, may be a more important factor than the properties of the tab material.

A number of buckling analyses of compression specimens have been performed, which have given considerable guidance on requirements for avoiding premature buckling failures. Brooming which is a frequent problem in end loaded compression specimens is probably not well understood and needs further investigation. Sandwich beam compression specimens have been analyzed to examine the degree of restraint between the core and composite skin being subjected to compression testing.

Considerable stress analysis has been reported for shear test specimens. In the case of in-plane shear tests, stress analysis has been conducted on a number of specimen designs such as the $\pm 45°$ tension test, the Iosepescu test, the rail shear test, the picture frame shear test, the double notched shear specimen and others. The double-notched shear specimen is a good example of a design based on an oversimplified concept of the stress state in the specimen which is not even approximately achieved in practice. Because of extremely high stress peaks in such specimens, all test results obtained from them must be considered suspect. Stress analyses have also been performed on beam-type specimens such as the short beam shear test for transverse shear properties to determine the effect of stress peaks around the load points.

Specimen Machining and Alignment Effects

Machining tolerances for test specimens may be somewhat arbitrary. A rational basis for setting tolerances may be developed from parametric studies of the effects of specimen machining errors, i.e. computer modelling of the influence of non-planarity and non-paralellism of specimen surfaces on the stress state in the specimen. Such studies have been presented in the literature to some extent, especially in the case of compression testing where the concern for sensitivity of test results to specimen imperfections is generally prevalent. Specimen alignment is a crucial feature of many test methods, again, especially in the case of compression testing. Some testing jigs have provided special features for insuring precise specimen alignment. As in the case of machining tolerances, requirements for alignment are often specified arbitrarily, and there is a need for combined experimental and analytical studies to establish these requirements more rationally in several types of test.

FORMAT OF THE DOCUMENT

The preceding discussion illustrates the type of information that this report is intended to provide. Each of the 3 volumes a provides comprehensive review of most of the test methods which have been used for obtaining structural properties of composite materials over the years. These include most of the standard methods which have been adopted by ASTM, SACMA (Suppliers of Advanced Composite Materials Association) as well as other organizations, in addition to a number of methods which have become generally popular in the industry but have not been adopted as standards.

The format of each volume includes the following:

1. EXECUTIVE SUMMARY (constitutes a brief summary of the state of testing methodology for the type of testing addressed in the volume under consideration)

2. INTRODUCTION

3. SUMMARY AND RECOMMENDATIONS (includes a relative ranking of test methods in each category, and recommendations for effort needed to correct deficiencies)

4. DETAILED DISCUSSION (a detailed discussion of each test method under consideration, including: failure characteristics of the specimen; discussion of the status of stress analysis for the specimen considered and conclusions to be drawn about the effect of stresses on test results and; practical considerations such as sensitivity to machining tolerances, specimen alignment requirements, etc)

In addition, an appendix is included with each volume which contains an annotated bibliography covering all of the available literature back to the mid 60's which it was practical to review within the scope of this effort.

TECHNICAL SUMMARY

Test methods for determining in plane and interlaminar shear response of unidirectional and laminated fiber composites are reviewed based on the literature listed in the Appendix. The state of the art and relative rankings of different methods are summarized in Tables 1 and 2. Based on the review, the following points appear noteworthy.

INPLANE SHEAR

(i) Initial shear modulus can be determined using most of the test methods provided appropriate correction factors are used to determine shear stress in the test section based on stress analyses reported in literature.

(ii) Ply cracks and other subcritical damages, which result in nonlinear stress strain response of unidirectional composites usually grow at different rates depending on the fiber orientation or lay up (0°, 90° or 0/90° cross ply) as well as the test method. For example, the off-Axis Tension test often yields very low ultimate stress and strain for common brittle epoxy systems. The use of cross ply lay up in Torsion Tube, Iosipescu or Rail Shear tests results in slow constrained damage growth (increasing number of ply cracks with increasing load) which is considered by many workers as the pattern expected in application laminates. Similar behavior is also expected in God Rail Shear and thick (>32 ply) a Tension test specimens. Thinner a Tension specimens yield low ultimate stresses and strains in common graphite-epoxy composites. Additional studies are suggested to address these issues.

(iii) Simple modifications to some of the methods may yield better specimen performance. For example, redesigning the grip regions in solid torsion specimens appears worthwhile. on the other hand, significant modifications may be required in some other methods such as Picture Frame or Crossbeam.

(iv) The ±45° Tension test is possibly one of the simplest tests to conduct and is usually favored in the industry. Recently, the Iosipescu test has gained wide acceptance, although special fixtures and some care in specimen preparation and testing are required. A small number of investigators prefer Rail Shear tests, especially for cross ply and other lay ups. However, care in bonding or bolting the rails to the

Table 1. Status of Inplane Shear Test Methods

Layups	Method	Status	Rank •
0°	$(\pm 45°)_{ns}$, Tension, ASTM D3518 SACMA SRM 7-88	Ultimate strength and strain not acceptable except for thick specimens. Study required for effects of tabs and thickness. Effects of transverse tension may be important in some cases.	2
	Iosipescu, ASTM Standard Approved by D-30 Committee	Acceptable. Correction factor required. Measurement of all strains with rosettes and back to back gages may be required.	1
	Rail Shear - Rectangular or Parallelogram, ASTM Guide D4255	Controlled 0° tests required. 90° tests appear to yield good data. Measurement of all strains may be required.	1
	Torsion - Circular Bar	Acceptable, but ultimate strains appear to be lower than Iosipescu and rail shear. Data reduction procedure is simple but needs approval from composites community. Machining required. Damage progression needs study.	2
	Torsion - Rectangular Bar	Acceptable, but ultimate strains appear to be lower than Iosipescu and rail shear. Data reduction procedure is complicated. Damage progression needs study.	2
	Torsion Tube, ASTM Standard under Development	Excellent, but expensive. Ultimate stress and strain levels high for fibers parallel to longitudinal axis of tube. Effects of this and other fiber orientations (hoop and slightly off from hoop) should be compared.	1
	Off-Axis Tension	Acceptable only for modulus, correction factors based on aspect ratio required.	--
	Picture Frame or Cross Beam	May be acceptable but more studies required. Tests are highly complicated.	--
	Slotted Shear, ASTM D3846	Not acceptable for material property testing, possibly useful for quality control.	--
	Slotted Tension/ Compression	Appear promising. Further studies required.	--
$(0/90)_{ns}$	Iosipescu and Rail Shear	Acceptable, but measurements of all strains with rosettes may be required.	1
$(\pm 45)_{ns}$ and $(0/\pm 45/90)_{ns}$	Iosipescu and Rail Shear	Correction factors required. Problems in testing specimens with large thickness. Stress distribution complex. Measurements of all strains required. Not acceptable at this point.	--

• Rank 1 - may be acceptable in present form with little additional study. Rank 2 - may be acceptable with some modifications and comparative study. Some stress analysis with imperfections, damages, fixtures and/or tab end effects will also be useful.

Table 2. Status of Interlaminar Shear Test Methods

Method	Status	Rank
Iosipescu, ASTM Standard Approved by D-30 Committee	Thick specimens with bonded layers required. Appears to be the best choice for unidirectional or fabric composites. Laminates may suffer from free edge effects because of small width.	1
Short Beam Shear, ASTM D2344, SACMA SRM 8-88	3-point loaded specimens not acceptable because of local failure near loading points and strong influence of bending stresses. 4-point loaded specimens with optimized dimensions may perform better.	--
Other	Button torsion, double lap shear, slant shear and block shear all have problems with stress distribution. A parallelogram shaped double lap shear specimen with strong adhesive bonds may be acceptable.	--

specimens is needed for such tests. The Torsion Tube is the only test suitable for filament wound cylinders, but for obvious reasons it is not favored for obtaining lamina or laminate properties. Torsion tests on solid bars are simple, but data reduction procedures are complicated in the nonlinear range because of nonuniform stress distribution and for this reason they have not gained acceptance.

INTERLAMINAR SHEAR

(i) Iosipescu tests with specimens prepared by bonding several layers of a material appear to be the only available method at this time for determining interlaminar stress strain response. Obviously specimen preparation needs some effort and the quality of the bond may affect the results in some cases.

(ii) Short Beam Shear is one of the simplest test to conduct and it is often used, but test data are usually not accepted as material shear properties, since failure can be influenced by flexural and contact stresses. Further studies are suggested for three- and four-point loaded Short Beam as well as Lap Shear tests used for measuring shear strengths.

(iii) Slotted or Notched Shear test is possibly most economical, and for this reason it is often used for quality control purposes, but the results are influenced by the severity of stress concentration at the notches. Because of the economy and wide usage, additional studies are suggested for possible improvements of the test and careful comparison of test data with those from other tests.

In summary, it can be noted that a few standards are either available or under development for some inplane shear test methods. Further work is suggested for improving the $\pm 45^\circ$ Tension test for inplane shear and three- or four-point loaded Short Beam Shear test (or some other reliable method) for interlaminar shear. In the meantime, it is hoped that the discussions and suggestions contained in this report will be useful in deciding on test methods, specimens, procedures and interpretation of data.

1. INTRODUCTION

The anisotropic nature of fiber composites introduces considerable complexity in shear testing, and a thorough understanding of the behavior of test specimens is essential before material property data generated from such tests can be used with confidence. The major problem associated with the specimens is the difficulty in attaining uniform stress states within the test section. Other problems are created due to (i) inhomogeneity, (ii) various coupling effects like shear extension coupling in laminates, (iii) interaction of various failure modes and subcritical damage growth, and (iv) nonlinear shear stress strain response.

This volume describes the state of the art of inplane and interlaminar shear test methods obtained from a literature search. The Appendix contains an annotated bibliography of the works reported in literature. Many of the bibliographical entries are also directly referenced in the discussions presented in the report. These are marked with an asterisk in the list of references, so that the interested reader can refer to the bibliography for more information. Description of different methods, discussions, and recommendation are based solely on review of these works. No additional research was conducted for preparation of this report. An Executive Summary is given in the preceding section. The following section gives a detailed summary of the state of the art and identifies areas where work appears needed. For each method, the following points are addressed in the Summary.

1. Problems associated with load introduction and free edges.
2. Uniformity of stress field.
3. Sensitivity to imperfections.
4. Acceptability of failure modes.
5. Simplicity and adequacy of data reduction procedure.
6. Specimen preparation and fixture requirements.
7. Consistency of results and other informations.

Detailed discussions of the methods listed below are given in the sections which follow. These discussions are appropriate for all fiber composite systems except where some characteristic differences for a specific material are noted.

1. Torsion Tube
2. Torsion of a Circular Bar
3. Torsion of a Rectangular Bar
4. (±45) Tension
5. Iosipescu
6. Arcan
7. Rail Shear
8. Off-axis Tension
9. Picture Frame
10. Crossbeam or Cruciform Specimen
11. Slotted Shear
12. Short Beam Shear

All the methods listed above may be used for inplane shear tests for unidirectional materials. Some of them can be used for other laminate configurations. The last two are commonly employed for interlaminar strength measurements. Iosipescu and Lap Shear tests may also be used for this purpose.

A short discussion on some methods which are not very common is given in the last section.

For each of the test methods mentioned above, the following issues are addressed.

a. GENERAL DESCRIPTION OF THE TEST METHOD - Description of the method and procedure, which are commonly used, including drawings of specimens and fixtures.
b. STRESS STATES AND FAILURE MODES - General nature of the stress state, representative results from stress analyses (if reported), disturbances and stress peaks at critical locations such as load introduction points (including effects of grips, tabs, fixtures and tab variations and problems in hot/wet testing). Common failure or damage modes and consistency of results are also discussed.
c. DATA REDUCTION - Data reduction procedure.
d. OTHER REQUIREMENTS AND MODIFICATIONS - Other considerations such as specimen machining tolerance and alignment requirements, effects of minor

imperfections (specimen, fiber geometry, etc.) and suggested variations of the method for improving specimen performance.

2. SUMMARY AND RECOMMENDATIONS

This section gives a summary of findings related to each of the important methods (discussed in the following sections) followed by some recommendations identifying areas of further work.

2.1 TORSION TUBE

1. Problems due to load introduction can be significantly reduced by bonding the tubes to internal and external grips. Stress analyses show that stresses near such grips are not as large as in the case of bonded tabs, and end effects decay very quickly. A gage length to diameter ratio of the order 2 may be adequate.
2. The stress state is practically uniform (for small thickness to diameter ratio) over a large volume of material. The test is ideal in this respect.
3. Effects of imperfections have not been reported. However, care is needed to detect buckling possibilities. Thickness may have to be increased to avoid this problem.
4. Hoop wound cylinders fail at a comparatively low strain level, which cannot be accepted as representative lamina behavior in a laminate where plycracks do not cause sudden catastrophic failure. Tubes with fibers parallel to the axis or a crossply (0°/90°) layup will be a better choice, but they are difficult to make.
5. Data reduction procedure is simple.
6. Test cannot be used for materials in the form of flat plates.
7. Data reported in literature are usually consistent in the linear range. For obvious reasons, ultimate strains and strengths depend on the fiber orientation, i.e., axial or hoop wound, the latter one being susceptible to catastrophic failure due to crack propagation in the hoop direction. Moduli, strengths and ultimate strains obtained in different laboratories participating in Joint Army-Navy-NASA-Air Force (JANNAF) [1] round robin (±89.5° orientation of fibers to axial direction) appear to be consistent.

2.2 TORSION OF SOLID CIRCULAR BAR

1. Grip regions are usually made square. Constrained crack growth starts from this region. Length to diameter ratio of 15 (or more) is required. End effects decay, but effect of grip regions has not been studied.
2. Stress state varies along the radius but is the same over a large length along the axis.
3. May not be sensitive to minor imperfections.
4. Although ultimate strains are usually higher than those from hoop wound cylinders, it is possible that even higher ultimate strains can be obtained by redesigning the grip regions and minimizing the possibility of cracks starting from these regions.
5. A simple data analysis procedure is available for linear as well as nonlinear response.
6. Machining is required. Test is suitable for comparatively thick plates but not for thin ones.
7. No data are available to reach any conclusion about consistency of results from different sources.

2.3 TORSION OF SOLID RECTANGULAR BARS

1. End effects decay, but length to width ratio of 20 (or more) may be needed to reduce effects of end constraints. Constrained cracks start from the gripped regions, but no analysis of stresses in those regions is reported.
2. Stress state varies in the cross-section but is practically independent of axial location over a large length along the specimen axis.
3. Probably not sensitive to minor imperfections.
4. Constrained splitting starts in the gripped region and extends toward the center. Ultimate strains are comparable to those from torsion of circular bars. As in the latter case, redesigning the grip regions may yield higher ultimate strains.
5. Data analysis is simple for linear elastic cases, but is complicated in the inelastic problem. Further work is required to simplify data analysis procedure in the inelastic range.
6. Although machining is not required, moderately thick specimens (24 plies) are needed.

7. No data are available to reach a conclusion about consistency of results from different sources.

2.4 $(\pm 45)_{ns}$ TENSION

1. End Effects are not important. Tabs are possibly not needed. It is not clear whether tabs have any effect on failure. Free edge effects do exist, but are possibly not critical with dispersed layups. 3/4" - 1" width is adequate.
2. Stress state is uniform over a large area except near the free edges, but for obvious reasons vary from layer to layer. Transverse tensile stresses exist in each layer and they increase with increasing ratio of transverse Young's modulus to axial modulus. It is, therefore, surprising that Gr/Ep fails at shear strain levels lower than that for Gl/Ep. Lower fracture toughness or poor fiber/matrix interface quality in Gr/Ep may be the reason.
3. May be sensitive to minor variation in fiber orientations, but the effect has not been quantified.
4. Mechanism of damage growth appears to be representative of lamina behavior within a laminate, i.e., generation of increasing number of ply cracks. However, damage initiates early and failure occurs at low strain levels when plies are lumped. Even with dispersed layups, low failure strains are obtained with small number of layers, since significant load redistribution from the thick layers (which crack early) to other layers which have less cracks (or crack later because of lower thickness) can not occur to prevent early failure. Specimens with 32 or more plies do not fail before hardening due to the occurrence of scissoring (> 5% shear strain level for Gr/Ep).
5. Data analysis procedure is simple, but may not be accurate for large crack densities.
6. Specimen preparation is not complicated and no special loading fixtures are required.
7. Results from various sources are usually consistent in the linear range. In the nonlinear range results may differ depending on the number of plies as discussed earlier.

2.5 IOSIPESCU

1. Load introduction can cause problems in gage section unless the loading points are placed away from this region. Use of 110° or 120° notch and larger specimens (3" x 0.75) with 0° fiber orientation is required for this reason. Edge effects near the notch can cause delaminations in laminates with ±45° layers on the surfaces. For unidirectional (0° and 90°) or cross ply layups, edge effects do not play a major role. Local crushing can occur near loading points for ±45 layups. It is not clear whether tabs used to avoid such crushing cause any undue stiffening.
2. Stress state is uniform over a small region, but the response is found to be comparable to torsion tube, solid bar torsion and rail shear tests. Combined stresses exist, but do not appear to cause early failure in gage section. Round notches are necessary. Appropriate correction factor is required for shear stress.
3. Imperfections can play a major role. Twisting is suspected to be the cause of early failure of 90° specimens. Flat loading surfaces and proper shimmings are required to avoid out of plane bending. Back-to-back gages should be employed to check for irregularities in loading.
4. Local splitting parallel to fibers occur near the notches in 0° specimens which causes load drops long before final failure. Such splitting is the result of stress concentration at the notch. Out of plane bending can contribute to early splitting. The splits, however, get arrested as they approach the loading points. Cross ply specimens also show some minor splits but without any load drops. Such specimens also show many small cracks (constrained ply cracks parallel to fibers, which are created due to shear) which is the damage mode expected in a laminate. Similar cracks are often not noticeable in 0° specimens, possibly because of large splits, but it is likely that microcracks do occur to yield a nonlinear shear stress-strain response. It appears that damage modes in 0° and (0/90) specimens are acceptable, but 90° specimens fail early due to the easy fracture path available between the notches and this does not appear to be a valid mode of failure in a ply within a laminate.

The method seems adequate for 0° and (0/90) specimens. (±45) specimens may fail under loading points. Testing of (±45) and quasi-isotropic layups is difficult because of the high loads required for failure.

5. Data reduction is simple, but three-element rosettes may be desirable because of combined stress state. Some back-to-back gages should also be employed to check for out of plane bending and/or twisting effects.
6. Specimen preparation needs some effort and special fixtures are required.
7. The results from various sources appear to be consistent for 0° and (0/90) graphite/epoxy specimens if appropriate care is taken to avoid loading irregularities and proper correction for shear stress is used. It is not clear whether the high ultimate strains obtained are due to constraints imposed by the fixtures and/or non-uniformity of the stress state in the specimen. Inconsistency in the results has, however, been reported for metal matrix composites with large diameter fibers like boron. Such inconsistency may possibly be attributed to the small size of the gage section.

   The test has also been used for interlaminar shear properties for unidirectional and laminated or woven composites by making moderately thick specimens with bonded layers. It has been shown to be successful for unidirectional materials. For laminates, the results can be influenced by free edge effects because of small widths of the specimens.

2.6 ARCAN

1. No standard gripping procedure can be employed because of the shape of the specimen. Use of intermediate grips has been suggested. Edge effects near the notch may cause delaminations in some laminated specimens (as discussed in the section on Iosipescu specimens). Bonding of aluminum loading fixture to a small specimen of the shape of the notched test area may be difficult for laminates with high shear strengths.
2. Stress state in the test section may be acceptable [2] but it is complex slightly away from test section. No analysis is reported for small specimens bonded to aluminum fixtures with tabs.
3. Effects of imperfections have not been studied.
4. Failure mode of unidirectional specimens with fibers parallel to critical section is in the form of a straight cut (as in 90° Iosipescu specimen) and it is not acceptable. No result is reported about failures in other layups.

5. Data reduction procedure is simple, but correction factors (based on analyses) may be required for nonuniform shear stress distribution.
6. Specimen preparation is complicated.
7. Available data are limited to reach any conclusion about consistency of results.

2.7 RAIL SHEAR

1. Load introduction is a problem in two- as well as three-rail shear tests. Use of bolted rails and tensile loads may require retightening of bolts during loading. Bonded and tapered rails loaded in compression improve the situation, but stress singularities exist near loaded corners. Compliant adhesives may weaken this singularity to some extent. However, stresses remain high near the corners and unidirectional specimens with fibers parallel to rails (0° orientation) develop cracks near these corners, which may cause large scatter in test data and low strength. Artificially introduced cracks at these locations or the use of a parallelogram shaped specimen have been suggested to avoid this problem. For obvious reasons, such local cracking is not critical in 90° or (0/90) layups.
2. Stress state is fairly uniform over a large distance (width is usually ½" between rails) near the center of the specimen. However, axial as well as transverse stresses exist. A correction factor slightly higher than 1.0 is required to account for slight non-uniformity in shear stress.
3. Misorientation of fibers may affect the results, but the effects have not been quantified.
4. As discussed earlier, failure strains of 0° unidirectional specimens are usually lower because of cracks generated near the loaded corners. 90° unidirectional (fibers perpendicular to rails) and (0/90) layups fail at comparatively high strains after a considerable amount of constrained cracking, which appears to be an acceptable failure mode. Local compressive failure can occur in very thin 90° unidirectional specimens. Bond failure may occur in thick specimens and/or in layups which are strong in shear (quasi-isotropic or ±45 layup). Better adhesives and/or larger bond length may be utilized to solve this problem. The method is acceptable for 90° and (0/90) specimens with moderate thicknesses, such that compressive failure does not

occur near loaded corners. Although the method is attractive for quasi-isotropic and (±45) layups more tests are need for such layups.

5. Data reduction is simple, but three-element rosettes should be used because of the presence of combined stresses.
6. Specimen preparation is not complicated, but bonding tapered rails to the specimen is a very difficult process.
7. No conclusion can be made regarding the consistency of results from different sources. Ultimate strains are usually high for 90° and (0/90) layups as compared to torsion (tube or solid bars), but it is not clear whether that is due to constraints imposed by rails.

2.8 OFF-AXIS TENSION

1. End effects are important and have been studied in detail. Rotating end grips are required and correction factors (which depend on aspect ratio and off-axis angle) are needed to obtain correct shear modulus. This is the reason stiffer response has been reported in many past studies before such correction factors were calculated. Alternatively tab designs have been optimized or use of flexible tabs has been attempted.
2. Stress state is uniform over a large portion, but transverse tensile stresses are high and contribute significantly towards failure.
3. Slight differences in off-axis angle can cause changes in the response
4. Failure occurs under combined mode. Graphite/epoxy specimens have been observed to fail at very low strain levels, which is not acceptable. Use of failure theory has been suggested as a solution to the problem, but it does not appear to be the right approach for determining nonlinear shear response. Therefore, the test does not appear suitable if response in the nonlinear region is required.
5. Data reduction procedure is not very complex, but three-element rosettes are required.
6. The specimen is simple, but special rotating grips are required as described earlier.
7. With appropriate correction for shear stress, the results are consistent for moduli. Low ultimate strains have also been reported in most of the studies.

2.9 PICTURE FRAME

1. To avoid buckling possibilities, a sandwich with a honeycomb core is often employed. High stresses exist near the corners, where loads are applied through a loading frame. These areas are usually cut out. Doublers are applied near the specimen edges which are pinned at the corners.
2. Corner stresses remain high even with the modifications. However, the stresses can be reduced somewhat by placing the loading pins on the frames at the corners of the original specimen. Shear stress distribution, however, shows significant non-uniformity unless the doublers are very stiff, which is difficult to achieve in practice.
3. Effects of imperfections have not been studied, but buckling is to be avoided if a sandwich construction is not used.
4. Not much detail is available about the failure mode. Some researchers believe ultimate strength may be obtained accurately, because the shear stress is uniform in critical areas (near the edges) where failure initiates. Some workers feel that modulus can not be evaluated because of non-uniform shear stresses in the gage section.
5. Data reduction procedure is not complicated but it is clear that a correction factor is required to obtain the correct shear stress.
6. The specimen and fixtures are complicated. Biaxial loading is also required which is achieved through a complicated linkage system.
7. No conclusion can be reached about consistency of results.

2.10 CROSS BEAM OR CRUCIFORM SPECIMEN

1. To avoid buckling possibilities, the cross specimens subjected to tensile and compressive stresses in the two directions are often bonded to a honeycomb core. Load introduction does not pose any serious problem in the cross beam.
2. Past studies have dealt with (± 45) and (0/90) layups, the first for yielding the shear response of a (0/90) laminate and the second one giving the result for a (± 45) layup. Shear stress distribution in the first case is highly non-uniform and a correction factor is required for determining the shear stress at the center. Extensional stresses are high near the corners in both cases. Stresses in the cruciform and the cross beam face

sheets are found to be similar. Rounding the notches yields more acceptable stress distribution. Shear stiffness of the core is found to have some effect on the stress distribution in the cross beam.

3. Effects of imperfections (misorientation of fibers, etc.) have not been studied in detail. $(0/90)_{ns}$ cruciform may buckle and are sensitive to alignment.
4. Failure usually initiates near the corners and for this reason may not be an acceptable mode of failure.
5. Data reduction procedure is simple, but corrections are usually required as discussed earlier.
6. The specimen is complicated and fixtures for biaxial loading are required.
7. Modulus results are consistent but strength and ultimate strain may not be reliable except possibly in specimen with rounded corners.

2.11 SLOTTED SHEAR

1. Load introduction does not pose a problem.
2. Stress state is not acceptable - shear stress is high near the tips of the slots. Non-uniformity of stress and small specimen size make strain measurement impossible.
3. Results are strongly affected by the depth of the slots and it is often difficult to make the slots of depth equal to half the specimen depth. This is expected to be a more serious problem in specimens for determining interlaminar strength for which the test is commonly used.
4. The test specimen appears to be similar to mixed mode fracture toughness tests and, therefore, the failure mechanisms is not as acceptable as that causing failure under a more or less uniform stress state.
5. Curve fitting procedures appear to yield good strength data based on measurements from specimens with different distances between slots, but it can not be accepted as a measure of strength. The test may be used for quality control purposes.
6. The specimen needs precision cutting of slots.
7. No data base exists to judge the consistency of results from different sources.

2.12 SHORT BEAM SHEAR

1. Load introduction can cause local failure under the loading noses. Use of proper radius of noses, soft loading pads, and four-point loading can reduce severe effects of such local damages but only to a limited extent.
2. In addition to stress concentrations under loading points, existence of bending stresses complicates the stress state. Bending stresses can also be reduced by using the four-point loaded specimen. Non-uniform shear stress distribution and small depths (the test is commonly employed for interlaminar shear strength) make measurement of strains impossible. Due to nonuniform shear stress distribution along the midplane, shear strength is often over estimated (by the assumption of parabolic variation) and perhaps for this reason the test sometimes yield strengths comparable to inplane shear strengths.
3. Effects of specimen imperfections are not known, but probably not significant.
4. Failure often occurs in mixed mode and is also influenced by damage under the loading noses.
5. Data reduction is simple, but the assumption of parabolic shear stress distribution may not be always valid for strength calculation.
6. Specimen preparation is simple.
7. The test is simple and for this reason it is commonly used for quality control purposes. The results will possibly yield consistent data if all specimen parameters and load introduction methods (pads, nose radius, etc.) are kept the same. However, these parameters are often varied.

2.13 OTHER TESTS

Plate Twist, Four Point Ring Twist and Split Ring tests are usually suitable for determining the modulus and are useful in certain circumstances. It does not appear that these tests can be used for obtaining the shear response or the strength.

The Slotted Tension/Compression test is a specimen with slots at both ends subjected to biaxial load, i.e., tension parallel to the slots and compression on the other two sides (in the central region between the slots) and appears to be promising. It has been employed in one study and practically no data are available regarding the failure mechanism or consistency of results.

Button Torsion, Lap Shear, Slant Shear and Block Shear tests have also been used by some investigators for determining interlaminar shear strength. Stress states in these specimens are highly complex. Bond failures in Button Torsion and Double Lap Shear tests have been found to occur before specimen failure. Slant Shear specimens under compression do not fail in this fashion, but the results are found to depend on the compressive stress. A suitable design modification to the Lap Shear test (with parallelogram shaped specimens bonded to rails with strong adhesives) has been found to be successful in testing of carbon-carbon composites. Data from such tests are too scarce to reach any conclusion about the failure mode and consistency of results.

2.14 RECOMMENDATIONS

It should be noted that developments and modifications of the methods are still continuing. A "snapshot" of the status of all the methods at this point in time and some relative rankings are given in Tables 1 and 2. Based on the summary given above and the detailed discussions and results in the following sections, some areas of future work are identified below. These studies would be useful for improving specimen performance.

1. Stress analyses near gripped regions in Torsion tests (tube and solid bar) will be useful. Modification of gripped regions (with or without tabs) to control splitting of solid bars may be attempted. Damage growth in such specimens should also be studied. Differences in the response of axially reinforced and hoop wound cylinders should be quantified in a systematic manner.
2. Effects of small areas of uniform shear in Iosipescu and constraints imposed by rails in Rail Shear test should be studied via tests (changing dimensions) and/or stress analyses (modeling constrained damage growth and/or inelastic effects). Stress analyses of 90° Rail Shear specimens appear necessary for comparison with 0° results and correlation with test data. Suggested new modifications of these two tests should also be investigated. Tests are also needed to determine the adequacy of fixtures and

specimen sizes of $\pm 45°$ or quasi-isotropic layups which can be used in practice. Instrumentation requirements in both of these specimens need to be identified.

3. Thickness (number of plies) effects in $(\pm 45°)_{ns}$ Tension Test should be investigated analytically (modeling damage growth) as well as experimentally for various materials to confirm the results reported in literature and decide on the thickness to be used in practice.
4. The biaxially loaded Slotted Tension/Compression fixture may be studied further, provided the loading arrangement is not too complicated and expensive.
5. More analyses and tests are required to examine the performance of Short Beam Shear (3- and 4-point loaded) and Iosipescu specimens for determining the interlaminar strength and response. These tests, along with a bonded Lap Shear test with a parallelogram shaped section, as well as Slotted Shear specimens, should be investigated in future studies, since there is a need for a reliable interlaminar shear test.
6. Direct comparison of test results from selected methods for a fiber dominated and a non-fiber dominated layup will be useful. Use of crossply testing (instead of unidirectional) may be advantageous in some ways for determining inplane shear response of unidirectional materials.

3. DETAILED DISCUSSIONS

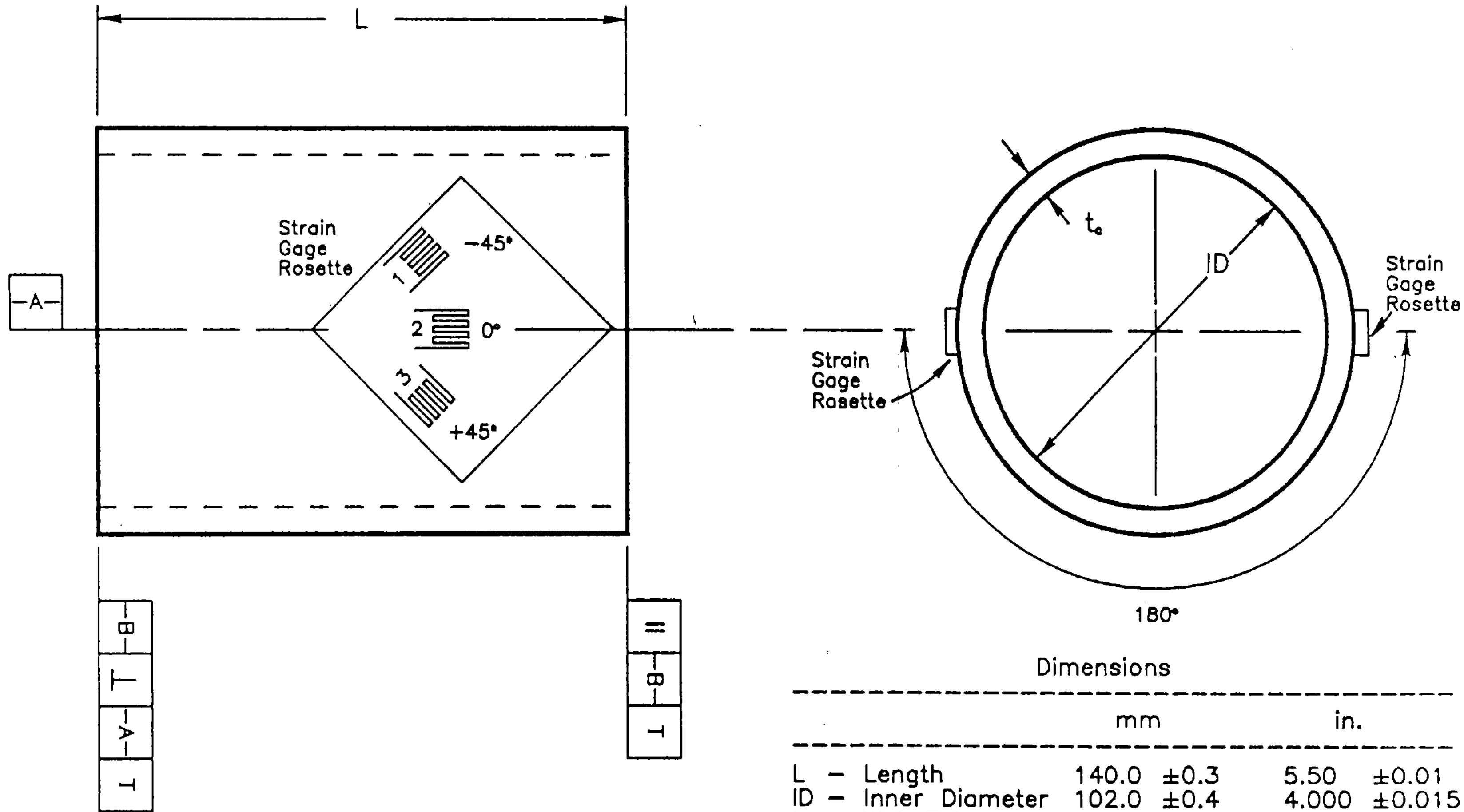
3.1 TORSION TUBE

3.1.1 General Description of the Test Method

Tests on thin tubes of various dimensions have been suggested by many investigators for determining the inplane shear response of unidirectional materials or laminates made of plies with different orientations. A specimen which has been found to perform well for hoop wound (±89.5) cylinders (in the Joint Army-Navy-NASA-Air Force sponsored round robin conducted as a part of MIL-HDBK-17 activities [1]) is shown in Figure 1. The specimen is bonded with a potting compound to end fixtures and devices to which torsional loading is applied (Figure 2). The gage length to diameter (L/D) ratio is unity. Suggested bond lengths at the ends are 0.75" for specimens of thickness 0.08". Thickness to diameter (T/D) ratio is 0.02. Use of at least two three-element strain gage rosettes (at -45°, 0°, 45° to the specimen axial direction) is recommended. Strain measurements are made at various values of the applied torque. It may be noted that testing of thin tubes has also been suggested for off-axis tension as well combined stress tests [3-5].

3.1.2 Stress States and Failure Modes

The stress state in a torsion tube is ideal for shear characterization except near the ends. Some analyses of the particular specimen configuration described above have also been reported. From the results in [1, 3-5], it appears that t/D ratio should be less than 0.02 so that the variation of stress though the thickness is small. Effects of external and internal gripping (of the type shown in Figure 2) on stress distribution in tubes with fibers at 30° to the axial direction (from [5]) are illustrated in Figure 3. The results indicate that shear stress disturbance (variation from gage section value) becomes small at a small distance from the grips, but the axial stress disturbance in off-axis specimens (with shear extension coupling) persists up to a distance equal to 20 to 30 times the thickness. Therefore, the L/D ratio of 1 suggested in [1] may be adequate for hoop wound tubes, although L/D > 2 is recommended in [4]. Stress distributions in tubes subjected to other types of loading are also reported

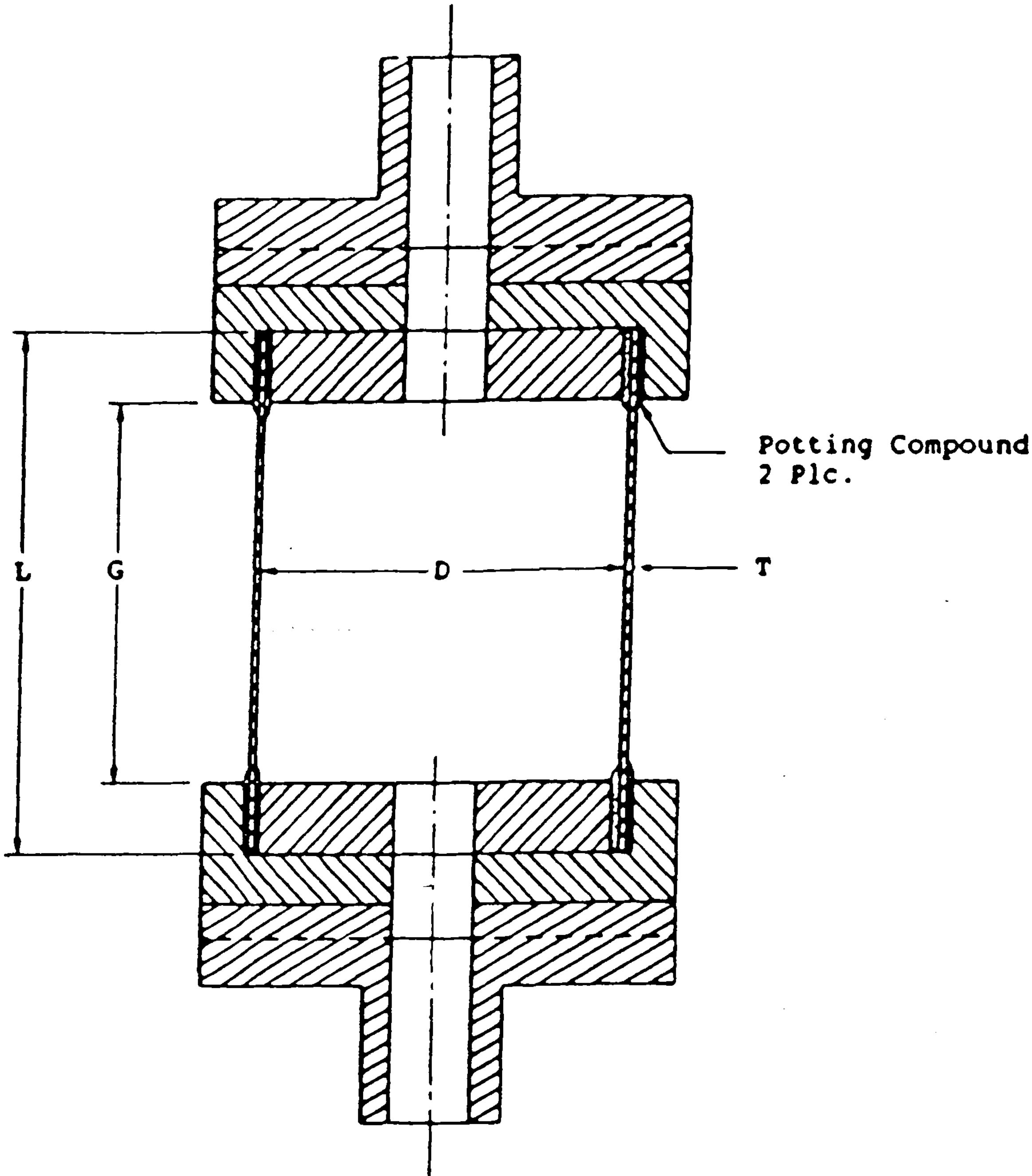


Dimensions

		mm		in.	
L	– Length	140.0	±0.3	5.50	±0.01
ID	– Inner Diameter	102.0	±0.4	4.000	±0.015
t_e	– Wall Thickness	2.0	±0.3	0.08	±0.01
T	– Tolerance	0.08		0.003	

Notes:
1. Tube may be fabricated on a tapered mandrel with maximum taper of 0.0005 in/in (0.0005 mm/mm) on the diameter.
2. Actual measure of inner diameter will depend on specimen placement along tapered mandrel during fabrication.

Figure 1. Torsion Tube Test Specimen Shown with Strain Gage Configuration [1]



Dimensions

	mm	in.
D - Specimen I.D.	102	4.00
G - Gage Length	102	4.00
L - Specimen Length	139.7 ±0.2	5.50 ±0.01
T - Specimen Wall Thickness	2.0 ±0.2	0.08 ±0.01

Figure 2. Specimen/Fixture Assembly for Torsion Tube [1]

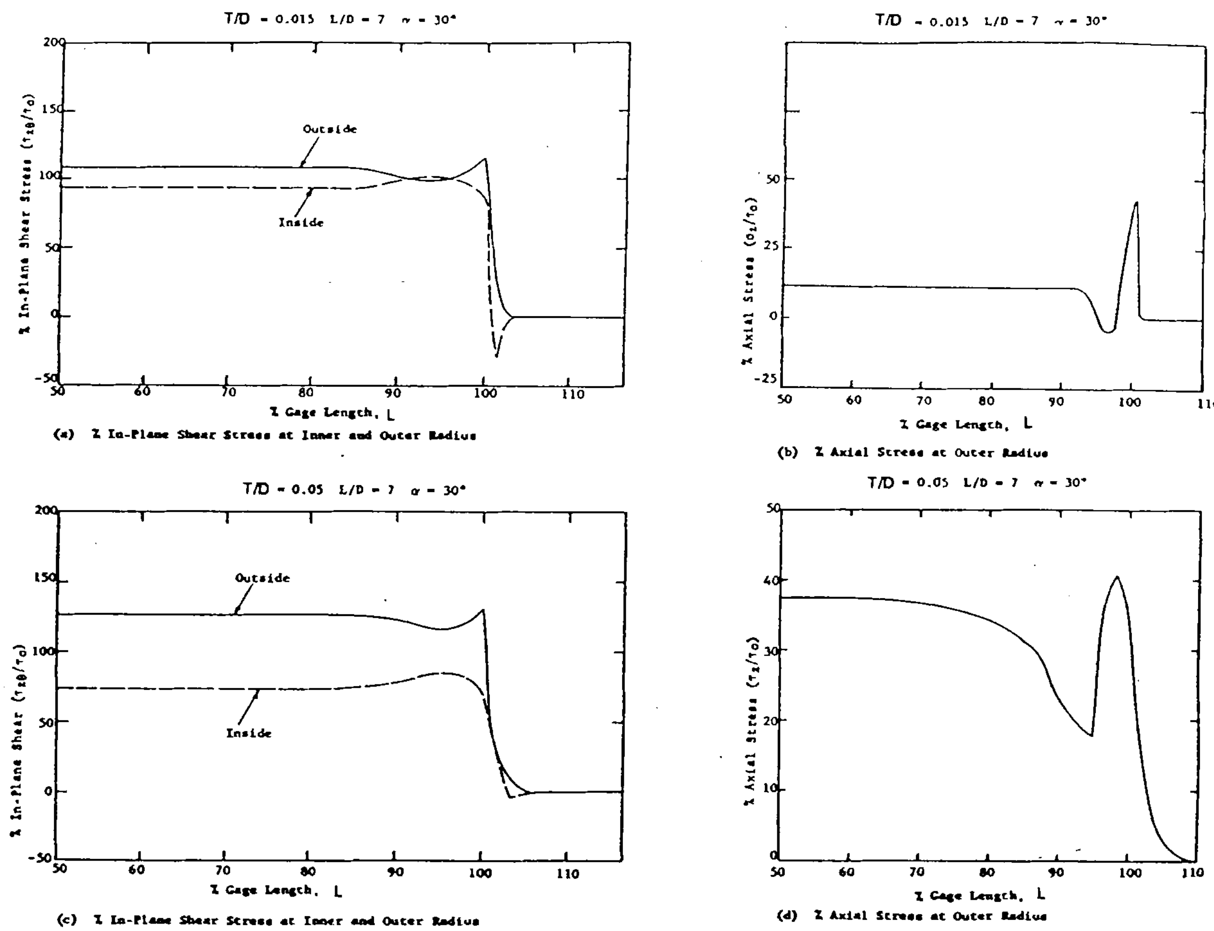


Figure 3. Normalized Stresses Along the Inner and Outer Radii for Torsion Tests [5]. Copyright ASTM. Reprinted with Permission.

in [5] and it is suggested that stresses under the gripping area, although not desirable, are less than those under conventional end tabs. Damage initiation may begin near the grips but load redistribution usually allows the specimens to carry loads well beyond damage initiation.

Commonly observed failure modes in hoop wound specimens shown in Figure 4 indicate that damages near the grips are not critical, since failure strains for such tubes are low because of easy fracture path (parallel to fibers) available. Test data reported in literature (and in round robin tests [1]) indicate that consistent results can be obtained. However, failure strains are usually higher in tubes constructed with fibers running lengthwise. Results from specimens of the latter type are usually comparable to those from other tests (0° Iosipescu or Rail Shear). Failure near the grips (or constrained splitting starting from gripped regions) is likely in such specimens. Buckling becomes a possible failure mode when the thickness-to-diameter ratio is small and the failure loads are high (as in ±45° material [6]). Local or global buckling can not be considered as an acceptable failure mode.

3.1.3 Data Reduction

The data reduction procedure is simple. The average shear stress is computed by the formula

$$\tau = Tr/J \tag{1}$$

where T is the torque, J is the polar moment of inertia and r is the average of inner and outer radii. This formula is accurate for small thickness-to-diameter ratios (t/D $\leq$ 0.02). Shear strains are determined from the average of shear strains determined from the strains measured at all rosette locations.

3.1.4 Other Requirements or Modification

No detailed study of tolerance requirements or imperfection sensitivity is reported in literature. It appears that a variation of less than half a degree in fiber alignment in axially reinforced or hoop wound tubes can be considered acceptable.

Various modifications of the specimen have been suggested. Thickening the zones near the grips or use of doublers may be advisable in some cases to avoid failure near the grips [7,

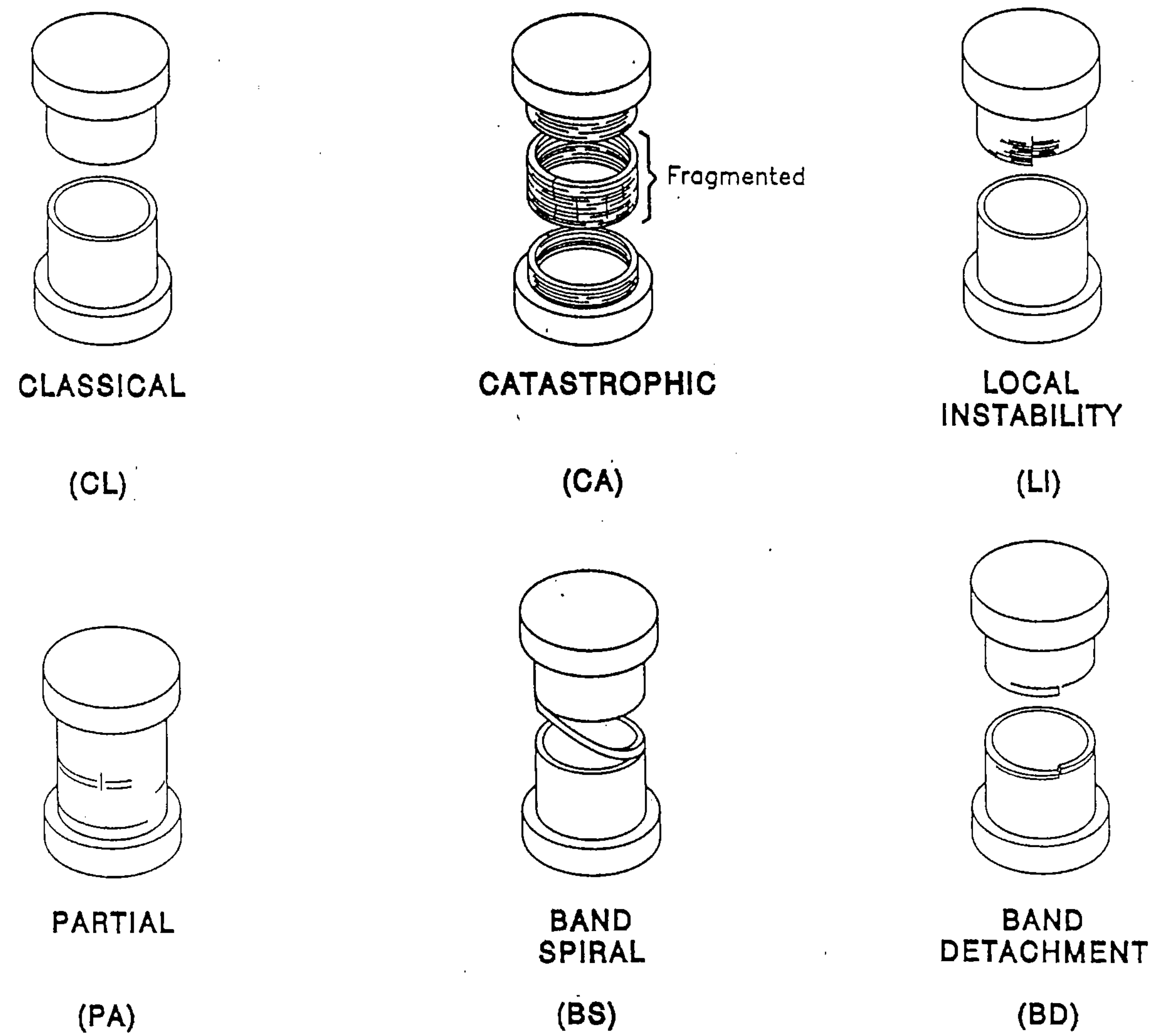


Figure 4. Failure Modes for Hoop Wound Tubes in Inplane Shear [1]

8] . Special fabrication processes are, however, required for this purpose.

The torsion test is advantageous when the material is made by the filament winding process. It can not be used to test materials made in the form of flat plates.

3.2 TORSION OF CIRCULAR BAR

3.2.1 Description of the Test Method

In contrast to thin tubes, testing of solid bars is easier to conduct and has been suggested by many investigators [9-12] for unidirectional composites. The specimens used are shown in Figure 5. For the purpose of strain measurements (rosettes are recommended; single 45° gages may also be used if no axial stresses are expected), bars of a minimum diameter of 0.25" (to be machined from 48 ply thick material) are possibly required. 0.25" and 0.4" diameter bars were used in [11]. The specimens were tested in INSTRON Model 1125 testing machining using three-jaw Jacobs chucks to apply a torsional load. The gripped length at each end was 1.75". No end tabs or other attachments are required. A minimum gage length-to-diameter ratio (L/D) of 16 is necessary. Larger diameter specimens used in [11] needed small flats ground at the ends to prevent slipping. An alternative is to machine the circular bars form 0.25" square bars leaving the ends square [10] as shown in Figure 5. Twist and strain measurements should be made near the center of the gage section for various values of the applied torque.

3.2.2 Stress States and Failure Modes

A uniform state of shear strain does not exist even in the gage section, since strain increases linearly from zero at the center to a maximum value on the surface. In the inelastic range the stress distribution is nonlinear. The non-uniform strain and stress distributions are, however, not a problem, since a simple data reduction procedure is available. The stress state is very complicated near the grips and, in the ideal elastic problem, a stress singularity exists at the grip boundary. Effects of end disturbance are expected to decay rapidly and test data

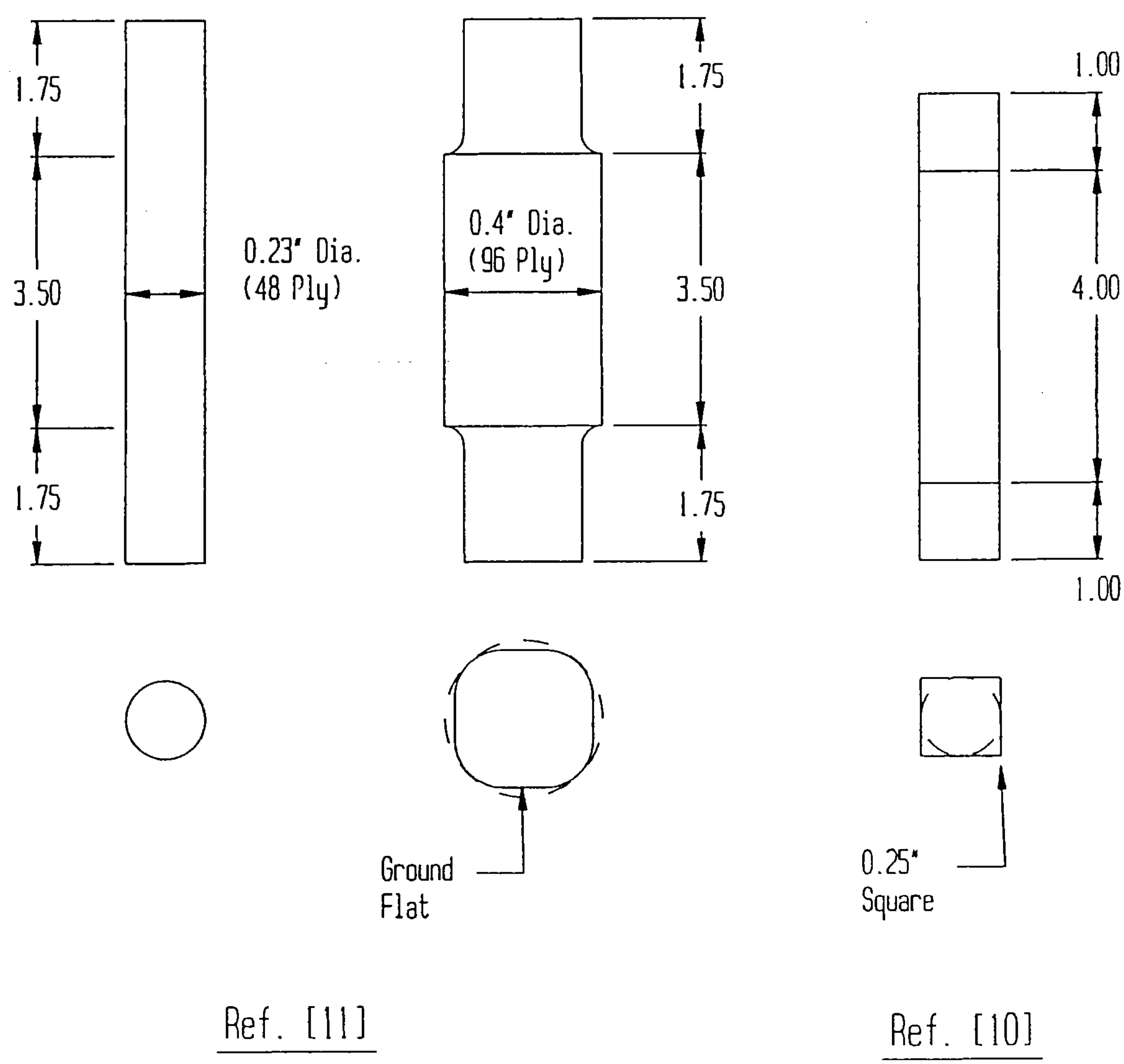


Figure 5. Circular Cross-Section Torsion Specimens

appear to indicate that for common graphite/epoxy composites L/D $\geq$ 16 will be required. Shorter lengths (L/D $\approx$ 10) may be adequate for modulus measurements. No stress analyses are reported in literature.

In common brittle matrix composite specimens, damage initiates near the grips. Axial cracks develop in the gripped section and extend radially inward as well as propagate to the gage section to some extent. In larger diameter specimens tested in [11], failures originated at the flats ground to facilitate gripping and none of the specimens failed in the gage section. For this reason test data are found to be comparable to those from Iosipescu and Rail Shear specimens up to the failure strains in torsion tests (3% as compared to 5% in latter specimens, see Figure 6). Therefore, the failure mode may not be an acceptable one (in the sense that development of one major crack causes failure in the gripped region), but since the shear response beyond 3% strain is very flat, the test data appear to be useful for practical purposes. Further, it is not clear whether stress redistribution from a highly stressed region to neighboring areas in Iosipescu specimen (or the constraints imposed by stiff rails in Rail Shear test) is the primary reason why such specimens survive to higher strain levels.

No data base exists to judge the consistency of results for different sources.

3.2.3 Data Reduction

A simple procedure for obtaining the nonlinear stress strain response from torque twist (or shear strain) data is described in Table 3.

3.2.4 Other Requirements or Modifications

Standard machining on a lathe to produce a bar of circular cross section is adequate. Smaller diameter bars can be machined with an aluminum oxide abrasive wheel in a tool post grinder mounted on a lathe [11], which produces excellent surface finish. Minor specimen imperfections may be tolerated without any serious problem in testing.

A modification of the specimen by making the gripped regions slightly larger (a square cross section is used in [10]) may be helpful for increasing the strain level for onset of cracking and thus the ultimate strains of the specimens. A smooth transition between the gage and gripped section is needed for this purpose.

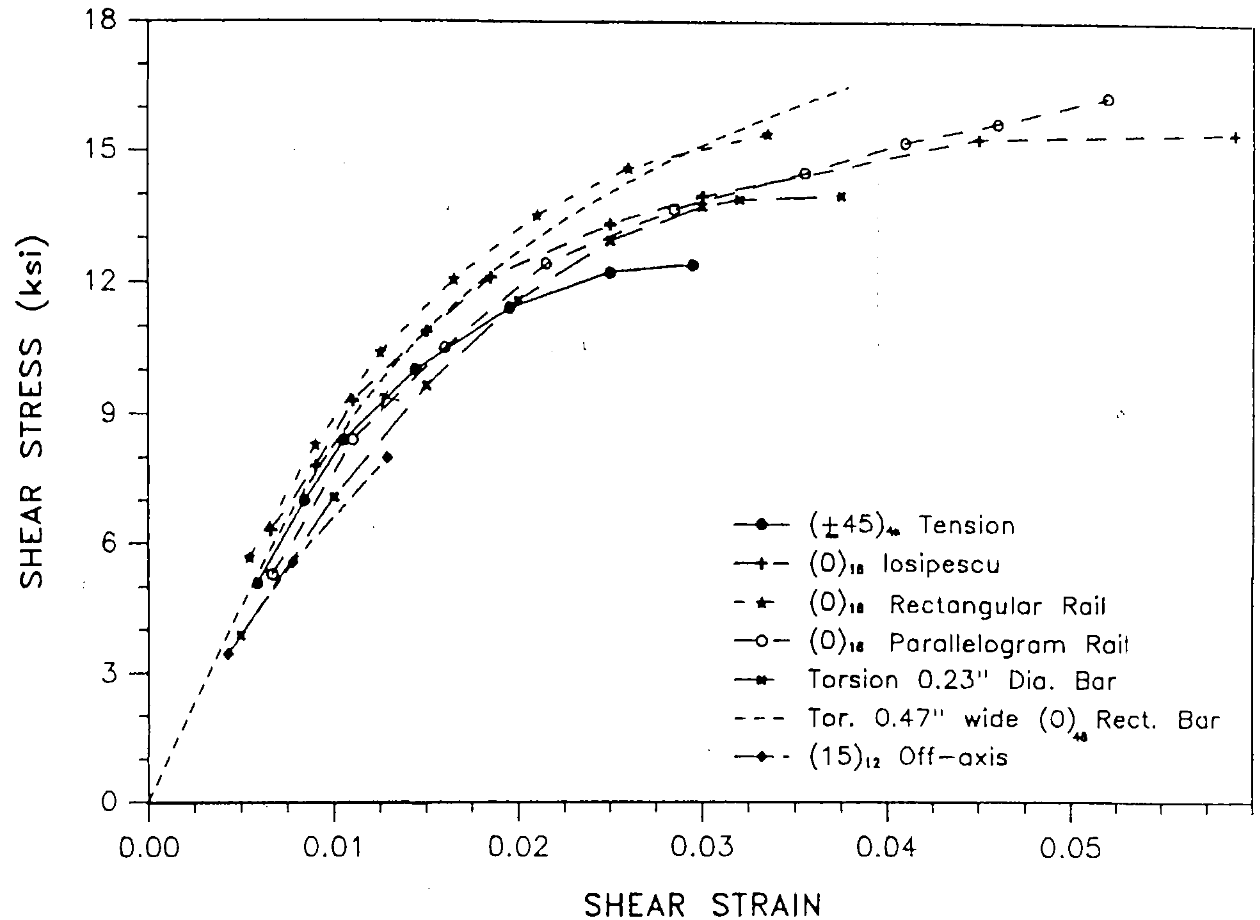


Figure 6. Representative Data from Different Inplane Shear Tests on Unidirectional AS4/3501-6 Specimens [11]

Table 3. Shear Stress-Strain Curve from Nonlinear Torsion Test Data [11]

$$T = 2\pi \int_o^a \tau(r) r^2 dr$$

$$\gamma = r\theta$$

$$\therefore T = \frac{2\pi}{\theta^3} \int_o^{a\theta} \tau \gamma^2 d\gamma$$

Let,

$$\tau = \Sigma b_n \gamma^n$$

$$T = \frac{2\pi}{\theta^3} \Sigma \frac{a^{n+3} b_n}{n+3} \theta^{n+3}$$

From test data and curve fit,

$$T = \Sigma c_n \theta^n$$

$$\therefore b_n = \frac{(n+3) c_n}{2\pi a^{n+3}}$$

Initial Shear Modulus = b_1

List of Symbols

a: radius of fiber composite rod
T: applied torque
r: radius
γ: shear strain
τ: shear stress
θ: angle of twist

3.3 TORSION OF RECTANGULAR BAR

3.3.1 General Description of the Test Method

To minimize machining requirements, the use of rectangular bars of unidirectional materials has been suggested by some investigators. The measurement of shear modulus from such tests is reported in [13]. Determination of the stress-strain response in the inelastic range is discussed in [11]. The specimen is of constant cross-section (2b x 2a). For ease in instrumentation for strain measurements, a minimum width (2b) of 0.5" is possibly required. 0.5 and 0.75" widths have been used in [11]. To reduce the stiffening effect due to axial stresses (stiffening at high shear strain level) width to thickness ratio should be of the order of 2 or less. Therefore, for 0.5" wide, specimens should be about 48 ply (.25") thick. The ratio of gage length to width (L/2b) should be of the order of 20. Twists and strains (three-element rosettes at -45°, 0°, 45° to specimen axis) should be measured near the center of the gage length. Torsional loads may be applied in a manner similar to those for circular specimens discussed earlier. However, one of the chucks should not be constrained axially to minimize axial stresses, which are unavoidable in these specimens.

3.3.2 Stress States and Failure Modes

Uniform states of shear strain or stress do not exist even in the gage section. In fact, they are more complicated than those in a circular bar, although they are constant over a large region away from the grips. An appropriate data reduction procedure can, however, be employed considering the variation of stresses over the cross section (as discussed later). Stress disturbances exist near the grips with stresses peaking at the grip boundary (not quantified by any stress analysis) as in circular bars which imply that sufficient length must be allowed for such disturbances to decay. In addition to these effects there are two other factors which influence the performance of rectangular bars as discussed next.

(i) Warping Constraints - Approximate calculations for thin cross-sections show that when the ends are not free to warp, axial stresses exist at the ends and the shear stresses as well as the rotation between the two ends are reduced. Approximate estimates of these reductions are given below for the elastic case.

$$\text{Percent reduction in maximum shear stress} = \mathbf{125\ exp}\ (-mz) \qquad (2)$$

$$\text{Percent reduction in rotation between ends} = 26\sqrt{\frac{E_A}{G_A}} \cdot \frac{2b}{L} \qquad (3)$$

where

z = distance from end

$$m = \sqrt{\frac{40\,G_A}{E_A}}/2b \qquad (4)$$

2b = width (greater than thickness)

E_A = axial Young's modulus

G_A = axial Shear modulus

L = gage length

For common graphite/epoxy composites, the reduction in rotation is more dominant and to achieve ideal performance large L/2b ratio is required. However, if twist (or strain) is measured near the center, length to width ratio of 15 is needed to insure a reduction of less than 0.5% in maximum shear stress and strain. Relative rotation between the ends is reduced by 8% for L/2b = 15. Larger length (L/2b ≈ 20) may be required for two reasons, namely: (a) to obtain reliable response in the inelastic range, and; (b) allowing sufficient distance from stress peaks at the grips discussed earlier.

(ii) Stiffening Effect Due to Axial Stresses - The torque required increases with increasing twist (or shear strain) and the increase over the torque neglecting stiffening is

$$\text{Percent increase in torque} \approx 0.833\ \gamma_{max}^2\ \frac{E_A}{G_A} \cdot \left(\frac{2b}{2a}\right)^4 \qquad (5)$$

γ_{max} being the strain at the center of the longer side (2b). It appears that if γ_{max} = 4%, width-to-thickness ratio (2b/2a) should be of the order of 2 or less to keep this increase within 0.5 percent for standard graphite/epoxy composites. The effect could be little more pronounced because of inelastic effects. It is not important for modulus measurement.

All specimens tested in [11] failed by splitting similar to those observed in circular specimens. Ultimate strains ($\approx$ 3.5%) were lower than those obtained from Iosipescu and Rail Shear tests (Figure 6). The response also appears to be stiffer since highest value of L/2b was of the order of 15. Lower L/2b ratios yielded stiffer response. None of the specimens failed in multiple pieces since the fibers ran lengthwise. Although this may not be an acceptable failure mode, responses comparable to those from other specimens may be obtained with L/2b of the order of 20. Further tests are, however, required to confirm this possibility. No data base exists to judge consistency of results from different sources.

3.3.3 Data Reduction

If the torque-twist curve is linear, the data reduction procedure is straightforward. In the case of nonlinear response, the following procedure provides a means of obtaining parameters for a Ramberg-Osgood description of the stress-strain curve [14].

I. The experimental torque-vs-twist curve of the type shown in Figure 7 can be used to define a dimensionless compliance S, for a given value of torque, T, and actual twist per unit length, θ, in terms of the secant twist compliance defined by θ/T. The relationship

$$S = Ga^4 \frac{\theta}{T} \tag{6}$$

where G is the initial (elastic) axial shear modulus, gives the desired nondimensional compliance S in terms of θ and T.

For the elastic case, this can be related to the expression for T vs. θ in terms of the polar moment of inertia, J, i.e.,

$$T = GJ\theta \tag{7}$$

and writing J as

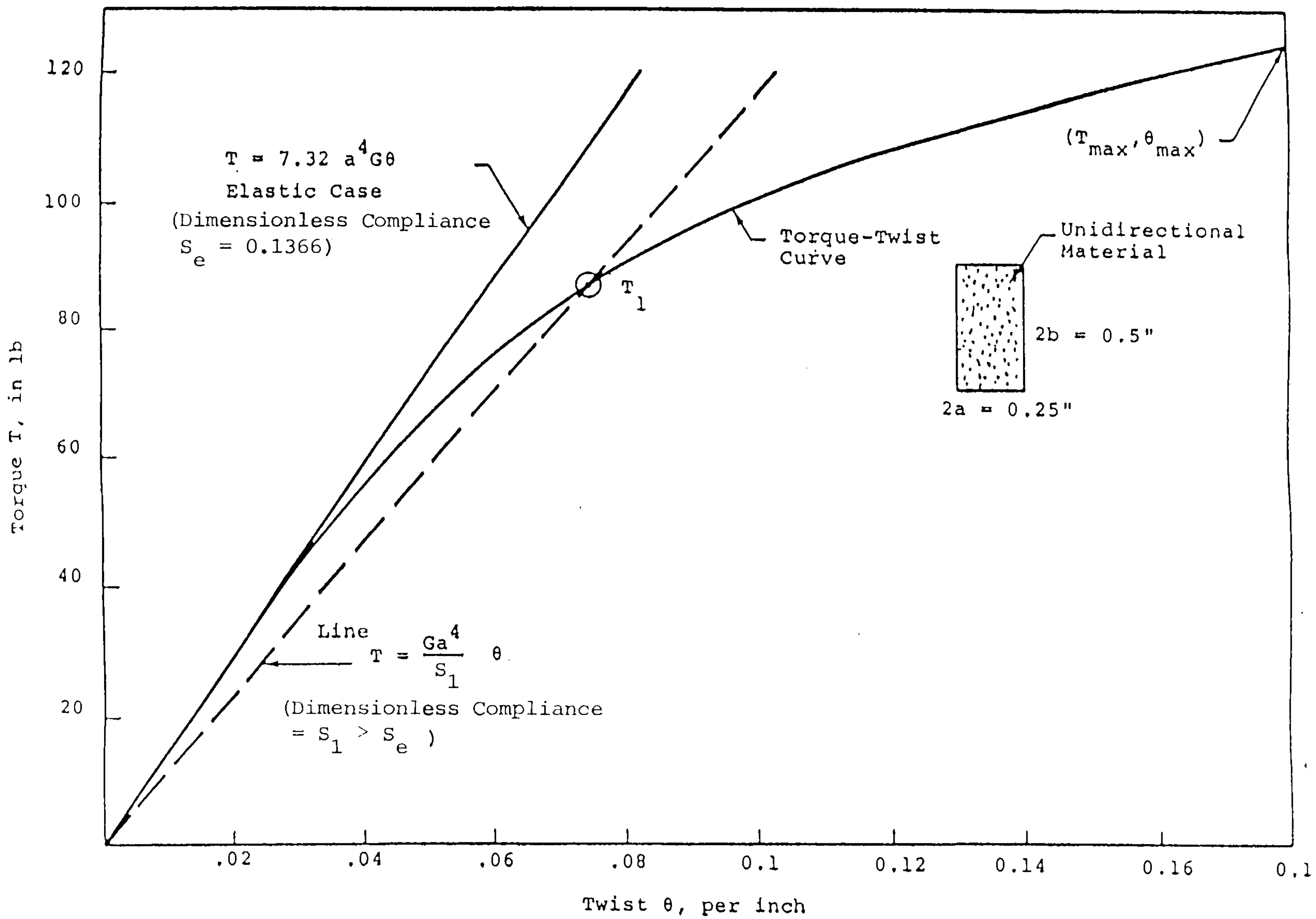


Figure 7. Experimental Torque Twist Plot of Torsion of Rectangular 0° T-300/Epoxy Bar [14]

$$J = K_o a^4 \tag{8}$$

leading to

$$T = K_o \,(Ga^4\theta) \tag{9}$$

From the classical elastic analysis for a rectangular bar of aspect ratio k = a/b (a<b) in torsion,

$$K_o = \frac{16}{3k} - 3.36\left(1 - \frac{k^2}{12}\right) \tag{10}$$

The initial value of S is, therefore,

$$S_e = \frac{1}{K_o} \tag{11}$$

II. Similarly, one can define a dimensionless torque, T′, by

$$T' = \frac{T}{\tau_o a^3} \tag{12}$$

where τ_o is the stress normalizing parameter of the Ramberg-Osgood constitutive relation

$$\gamma = \frac{\tau}{G}\left[1 + \left(\frac{\tau}{\tau_o}\right)^{\beta-1}\right] \tag{13}$$

III. The elastic-plastic torsion analysis given in [15] can be used to obtain a curve of T′ vs. S for several values of the exponent β, as illustrated in Figure 8 for a series of β's. Since S is determined from Eq(6) by θ/T, then an experimental torque-vs-twist curve such as the one given in Figure 7 allows a value of S to be determined for each θ -T pair. In addition, once β is assumed, the elastic-plastic analysis gives a value of T′ for each S. Obtaining T′ in this way at a given S, Eq(12) allows τ_o to be determined, after transposing it to

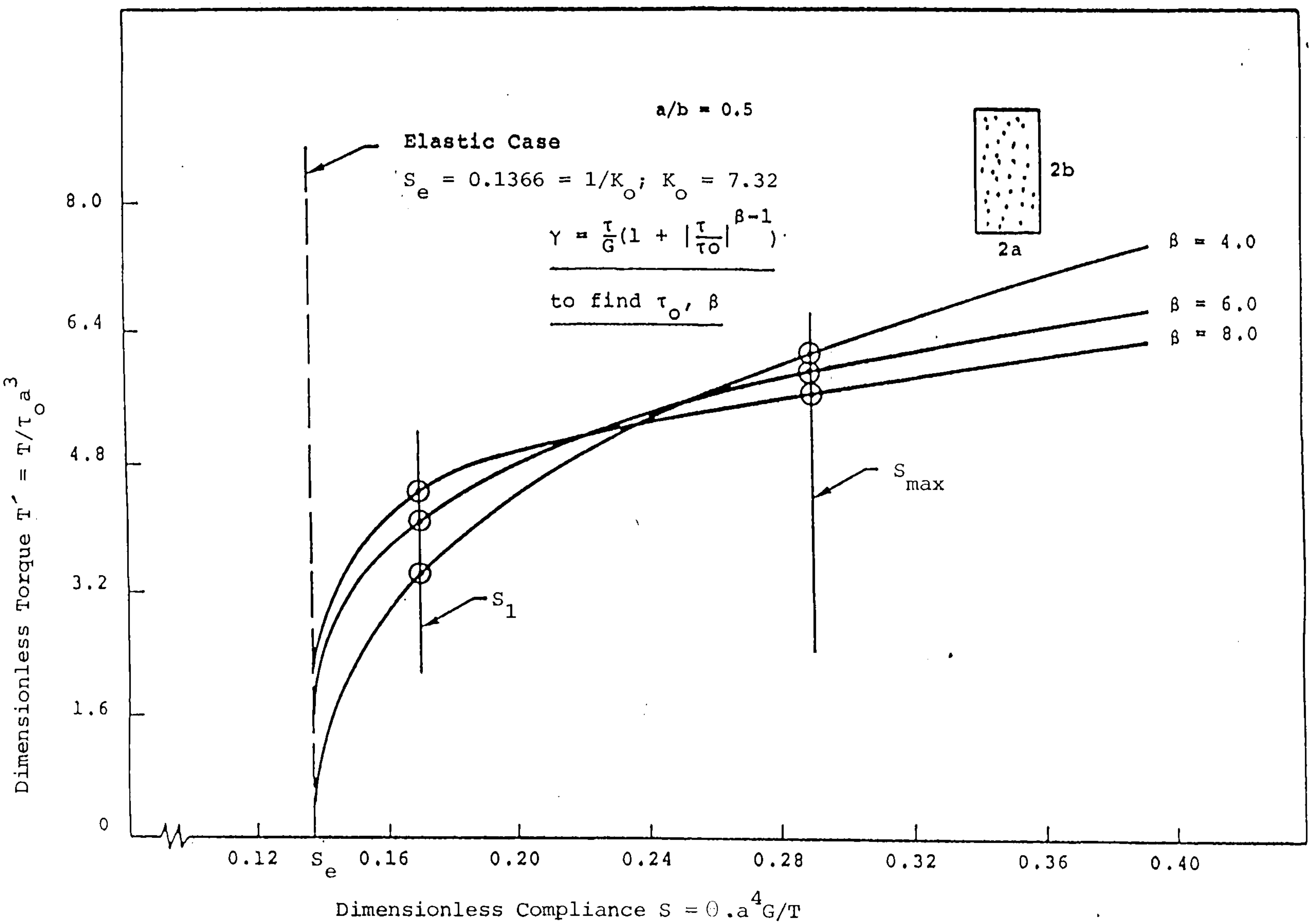


Figure 8. Analytical Non-Dimensionalized Plots for Data Reduction from Torque-Twist Curve [14]

$$\tau_o = \frac{T}{a^3 T'} \quad (14)$$

using experimental values of T for each θ or S.

IV. The exponent, β, can then be determined by varying it so as to get agreement in the values of τ_o obtained from (14) at at least 2 different values of θ along the experimental torque-twist curve. It is suggested that the two values include θ_{max} together with some intermediate value θ_1 for which S ($=S_1$) is greater than the initial value given in (11) by $1/K_o$, as shown in Figure 8.

In the following table, values of θ and T from Figure 7 are used to obtain corresponding S values, while the T values corresponding to θ are used to determine T/a^3. Subsequently, the theoretical curves of Figure 8 are used to give the T′ values corresponding to the observed T values, from which the relevant τ_o values are obtained using (14).

Experimental Data (Figure 7 - Initial S = 0.1366)		
Quantity	Point - 1	Point - Max
θ	.075	0.18
S	0.1706	0.2844
T (in-lb)	85	122
T/a^3 (ksi)	43.52	62.46
Analytical Results (Figure 8)		
	T_1'	T_{max}' (at θ_{max})
β = 4	3.40	5.971
β = 6	4.08	5.778
β = 8	4.48	5.508
Values of τ_o in ksi (Using (14))	at Point-1	at Point-Max
β = 4	12.8	10.46
β = 6	10.67	10.81
β = 8	9.71	11.34

A β value of about 6 gives the closest match in τ_0 for the two T-θ pairs, and would represent an appropriate selection of the Ramberg-Osgood exponent. Numerical interpolation of the above table could be used to get a more precise value. The procedure may be automated, if desired.

3.3.4 Other Requirements and Modifications

No machining other than cutting a bar of finite width is required. It appears that minor specimen imperfection may not have much influence on specimen performance. Modification or thickening of the end zones (keeping the width the same) may be attempted to examine whether higher failure strains can be obtained from these specimens. Use of tabs may also be tried for this purpose.

3.4 (±45°) TENSION

3.4.1 General Description of the Test Method

Uniaxial tension test of a $(\pm 45°)_{ns}$ laminate is a simple but accurate method for determining the shear modulus of unidirectional composites and is widely used in industry. An ASTM Standard D3518 [16] exists, which suggests the use of specimens as per ASTM D3039 for tension test (Figure 9). Commonly employed widths vary from ½" to 1". Use of tabs is usually not necessary for common organic matrix composites. Length between tabs for gripped regions is usually of the order of 6 to 8". Axial and transverse strains are measured using strain gages or extensometers.

3.4.2 Stress States and Failure Modes

It has been shown that the shear stresses (in layer coordinates) in each of the layers are equal to half of the average laminate stress [17-19]. However, in addition to the shear stress, axial (in fiber direction) and transverse tensile stresses exist in each of the layers. The layer stresses for unit applied tensile stress are presented in Figure 10 as a function of longitudinal and transverse Young's moduli of the layers [11, 14]. The stress distribution is, however,

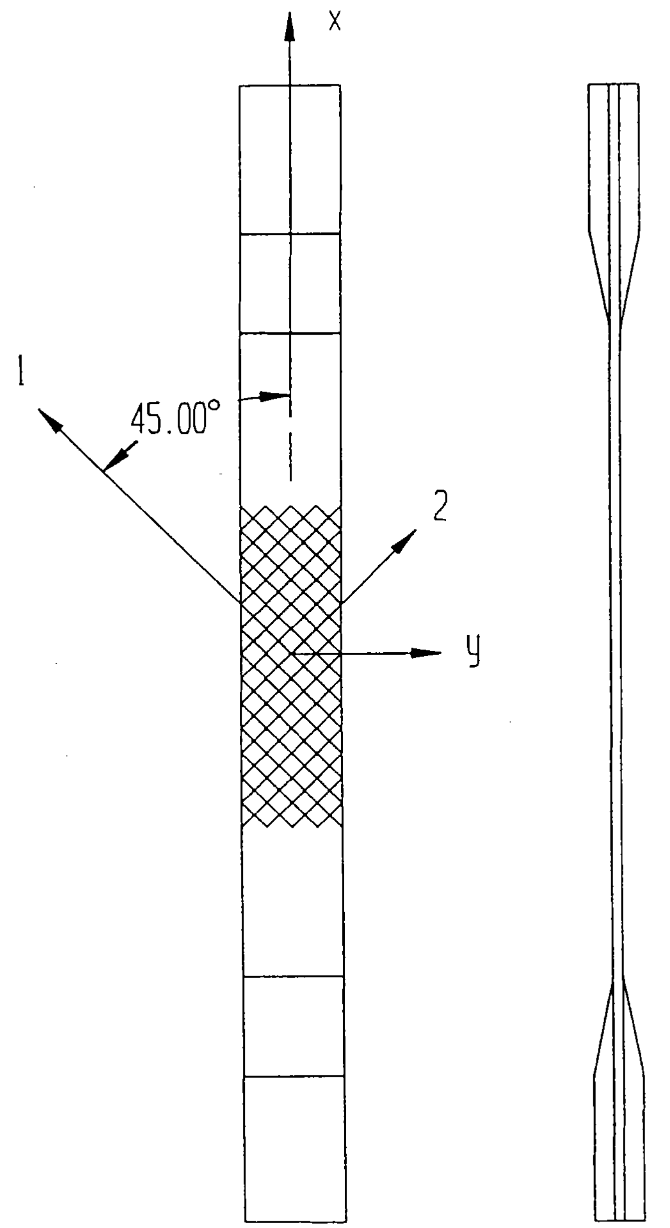


Figure 9. (±45) Specimen

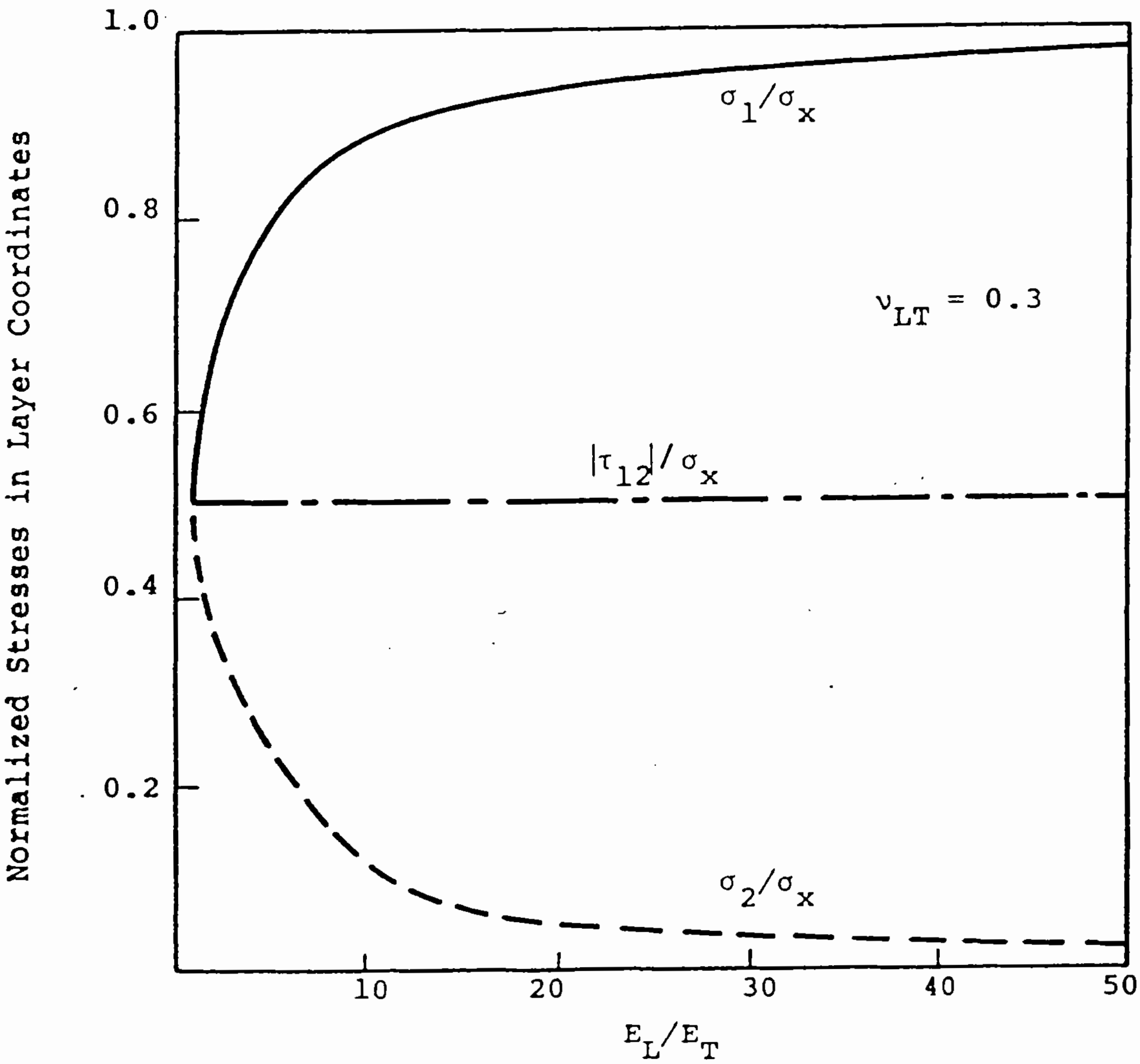


Figure 10. Normalized Layer Stresses Under Uniaxial Tension of $(\pm 45)_s$ Laminates [11, 14]

valid away from the free edges and the ends. End effects are possibly not of much importance and do not influence the results. Near the free edges, the strains and stresses in the layer can be different. The transverse tensile strain on the free surface can be higher [20] than those from lamination theory (see Figure 11). Edge effects, however, decay at a distance of the order of a ply or a layer (lumped plies of same orientation) thickness and for this reason responses obtained from specimens of different widths [11, 20, 21] are found to be almost identical.

It may be noted that ply stresses in the loading direction can differ because of naturally existing inhomogeneities or ply cracking caused by shear and transverse extensional stresses [20, 21]. The layer in the middle (2 plies thick) and those on the outer surfaces will develop such cracks early because of less constraint available from neighboring plies. In addition, the surface layers are more susceptible to cracking because of elevated transverse tensile strains near the edges as discussed in the previous paragraph [20, 21]. Partial redistribution of load (from locally cracked plies to neighboring plies) will cause changes in the stress state with increasing load. However, if there are not many plies other than the outer and inner layers, failure is expected to occur early. Severe strength reductions have been observed [22] when the layers are thick and lumped due to early development of plycracks as well as severe interlaminar shear stresses at the free edges (and also near the plycracks), which cause severe delaminations. Figure 12 shows such an undesirable failure mode in a MODII/5206 $(\pm 45°_4/-45°_4)_s$ laminate. Therefore, use of thicker $(\pm 45°)_{ns}$ specimens with dispersed layups (as opposed to $(\pm 45°_n/-45°_n)_s$) is recommended. It appears that the thickness should be of the order of 32 plies to obtain responses comparable to those from Iosipescu or Rail Shear tests. Some test data [20] (laminate stress σ_x vs. laminate strain ϵ_x) for various specimen thicknesses are shown in Figure 13. Stress analyses near isolated ply cracks and edge delaminations [11, 14] indicate that such damages are not critical for dispersed layups. It appears, however, slow and progressive ply cracking and development of some edge or internal delaminations (which develop after ply cracks and may connect them) cause a gradual stiffness loss. Significant load redistribution is possible in thick laminates with dispersed layups.

For specimens which are thin (16 plies or less), the load is found to reduce after a maximum is reached if the tests are displacement-controlled [20, 21]. On the other hand, in load-controlled tests, sudden failure will occur [11]. In any event, failures usually involve (i)

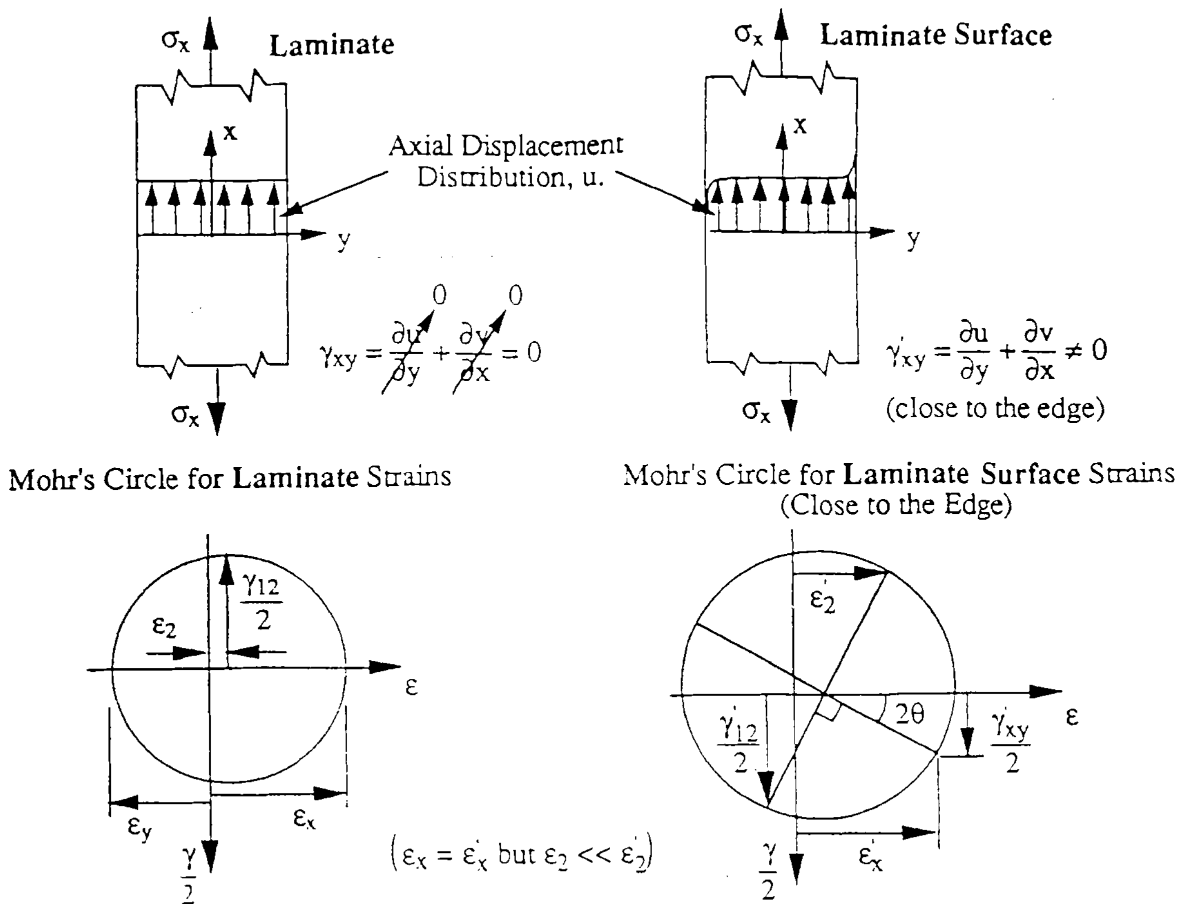


Figure 11. Strains in $(\pm 45)_{ns}$ Specimen and Edge Effects [20]. Reprinted with Permission

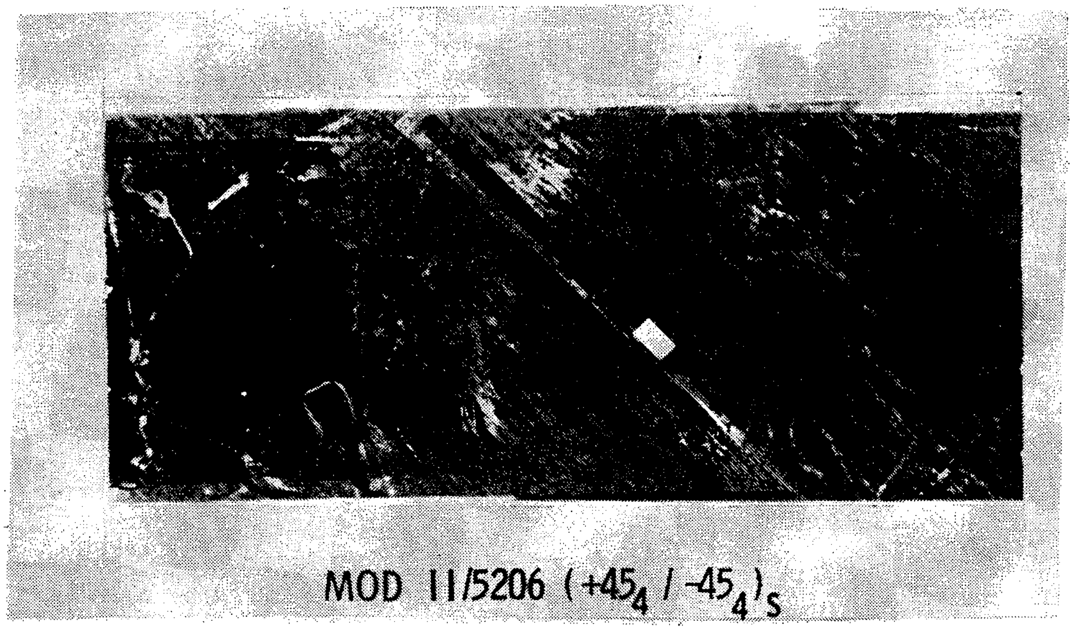


Figure 12. A Typical Undesirable Failure Mode due to Lumped Layup $(45_4/\text{-}45_4)_s$. Courtesy: D.W. Oplinger, FAA Technical Center

cracks along fibers in outer plies with some delaminated regions and (ii) fiber breaks in subsurface plies [11]. Sometimes the role of outer and subsurface plies are reversed and if the thickness is of the order of 16 plies, failure may not occur in all plies. However, in very thick laminates (> 24 plies), separation of specimens may not occur and stiffening is observed [20, 21] after 5 to 6% strain level (for graphite/epoxy) because of fiber scissoring effect (Figure 13). However, the response beyond the 5% strain level is not of practical interest. The mechanism of progressive damage (ply crack) growth appears to be representative of what may be expected in a laminate or structural component. Test data from different sources are usually consistent in the linear range. Responses, however, are different depending on the number of plies in the specimen as discussed above.

3.4.3 Data Reduction

The data reduction procedure is simple and well documented in ASTM D3518. It is based on the fact that under ideal conditions (no damage) the shear stress is given by [16]

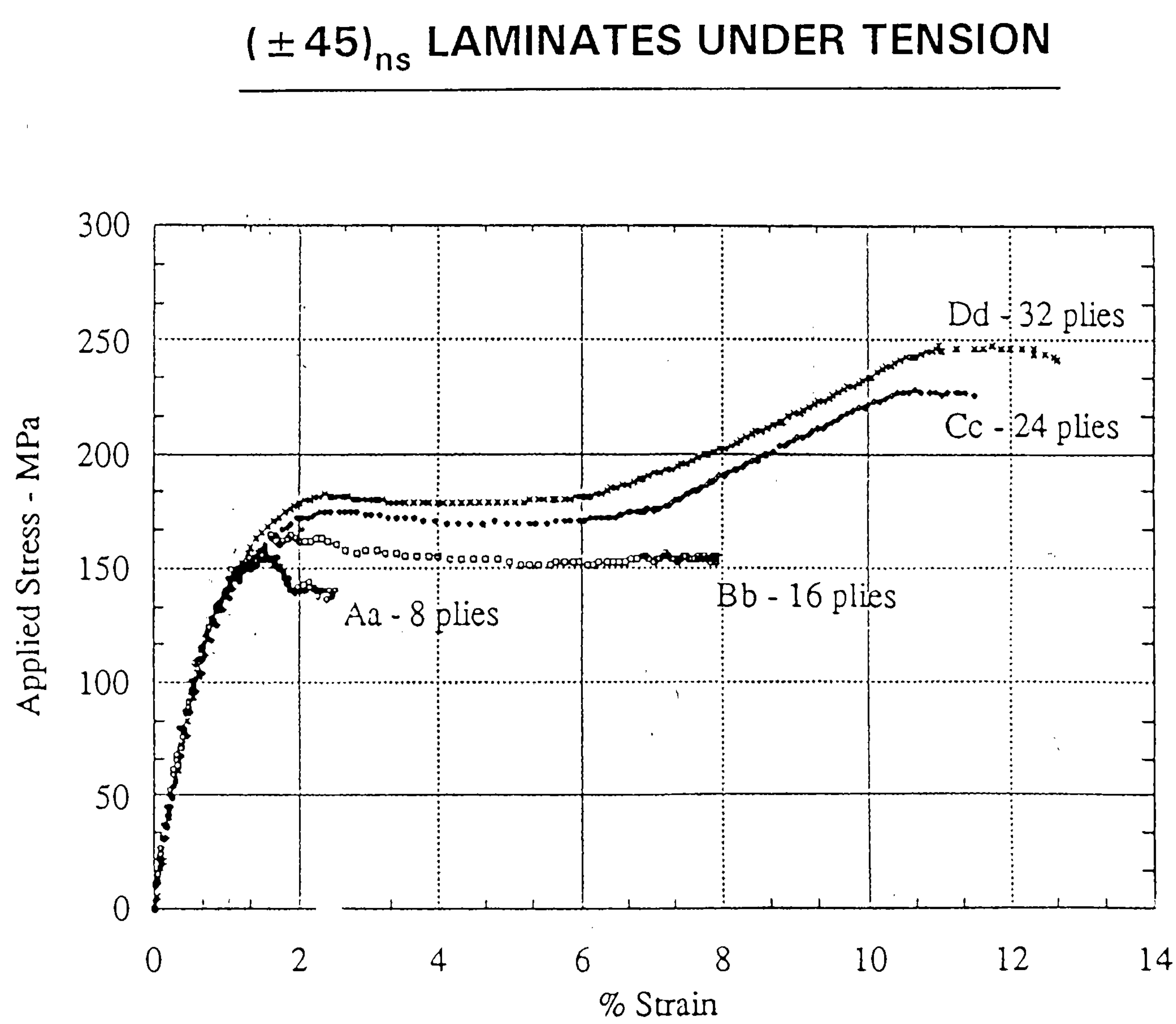


Figure 13. ±45 Tension Test Data [20]. Reprinted with Permission.

$$\tau_{12} = \sigma_x/2 \tag{15}$$

σ_x being the laminate tensile stress and the shear strain is expressed as

$$\gamma_{12} = (\epsilon_x - \epsilon_y)/2 \tag{16}$$

ϵ_x, ϵ_y being the axial and transverse laminate strains. Some questions, however, have been raised [20, 21] regarding the accuracy of the procedure when ply crack densities are high. Stress analyses with due consideration to damage development may be useful to resolve this issue.

3.4.4 Other Requirements or Modifications

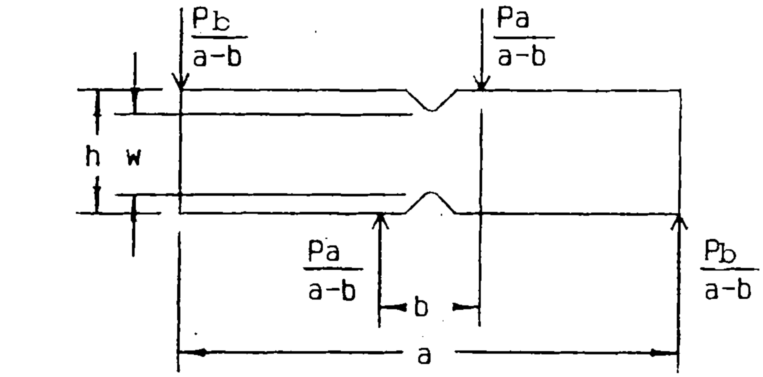
No special loading fixtures are required and there are no special machining requirements except for cutting. Fiber misalignments (off from ±45 and -45) will obviously influence the response to some extent. The effect has not been quantified. It appears, however, that ±0.5° difference is not significant. The requirement of higher thickness (≥32 plies as discussed earlier) has been identified recently [20, 21] and is not yet well accepted. Tests on other materials like glass/epoxy are needed.

Transverse tensile stresses in glass/epoxy composites (as obtained from laminate theory, see Figure 10) are higher than those in graphite/epoxy. Therefore, it is surprising that comparatively thin specimens ($(\pm 45)_{2s}$) of glass/epoxy fail at comparatively high strain levels [23] as compared to graphite/epoxy. Lower fracture toughness or poor fiber matrix interface quality in graphite/epoxy may be the reason for this difference.

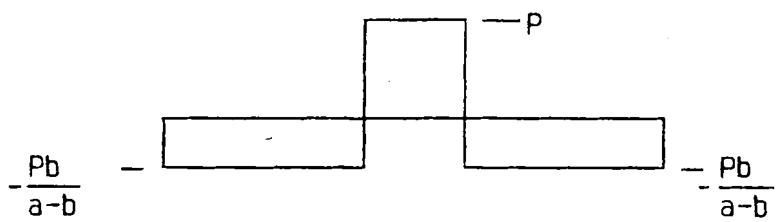
3.5 IOSIPESCU AND APFB

3.5.1 General Description of the Test Method

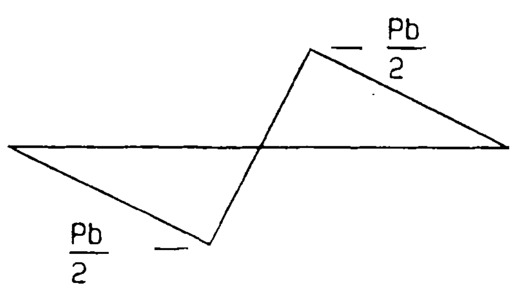
The shear test originally developed by Iosipescu [24] is accomplished by means of a four-point asymmetrical loading arrangement shown in Figure 14 [25], and for this reason it was given the name Asymmetric Four-Point Bend test [26]. In the central portion, the shear force



a. Force Diagram



b. Shear Diagram



c. Moment Diagram

Figure 14. Force, Shear, and Moment Diagrams for the Iosipescu Shear Test Method [25]. Reprinted with Permission.

is constant and bending stresses are small. In the center, an ideal situation of uniform shear stress exists in isotropic materials. Because of the small specimen size required, the test has become quite popular for determining shear response of unidirectional, laminated, woven fabric as well as chopped fiber composites. Various types loading arrangements and fixtures have been employed (see [26], [27]). The fixture which has developed after various modifications (most of them at the University of Wyoming [25]) performs quite well. Figure 15 is a photograph of the fixture. Details of the fixture are illustrated in Figure 16 [28]. A notched specimen (a 2" x 0.5" specimen shown in Figure 17) is loaded by comparatively rigid fixtures such that displacements are prescribed rather than the loads themselves. More recently a 3" x 0.75" specimen [25, 11] has been found to yield a better stress distribution. It has also been found that a 120° notch with a fillet radius of 0.05" and a notch depth of 20% of total at each end yield acceptable stress distribution in 0° graphite/epoxy unidirectional specimens (fibers along the beam length). Widths of 0.1" to 0.5" have been tested with the fixture.

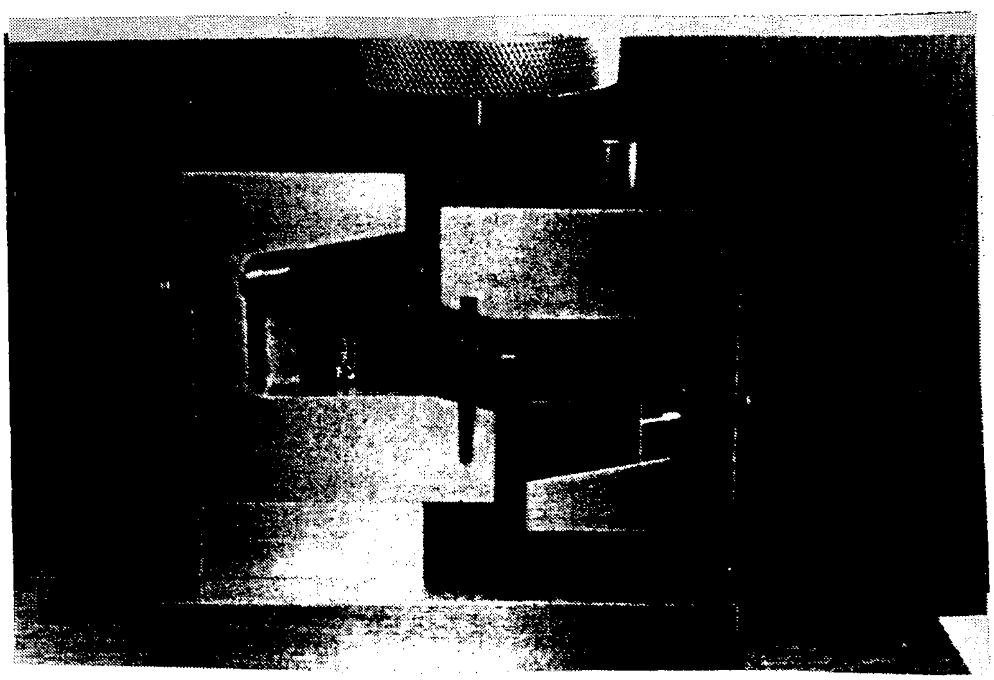


Figure 15. Photograph of the Modified Wyoming Test Fixture. Courtesy: D.F. Adams, University of Wyoming

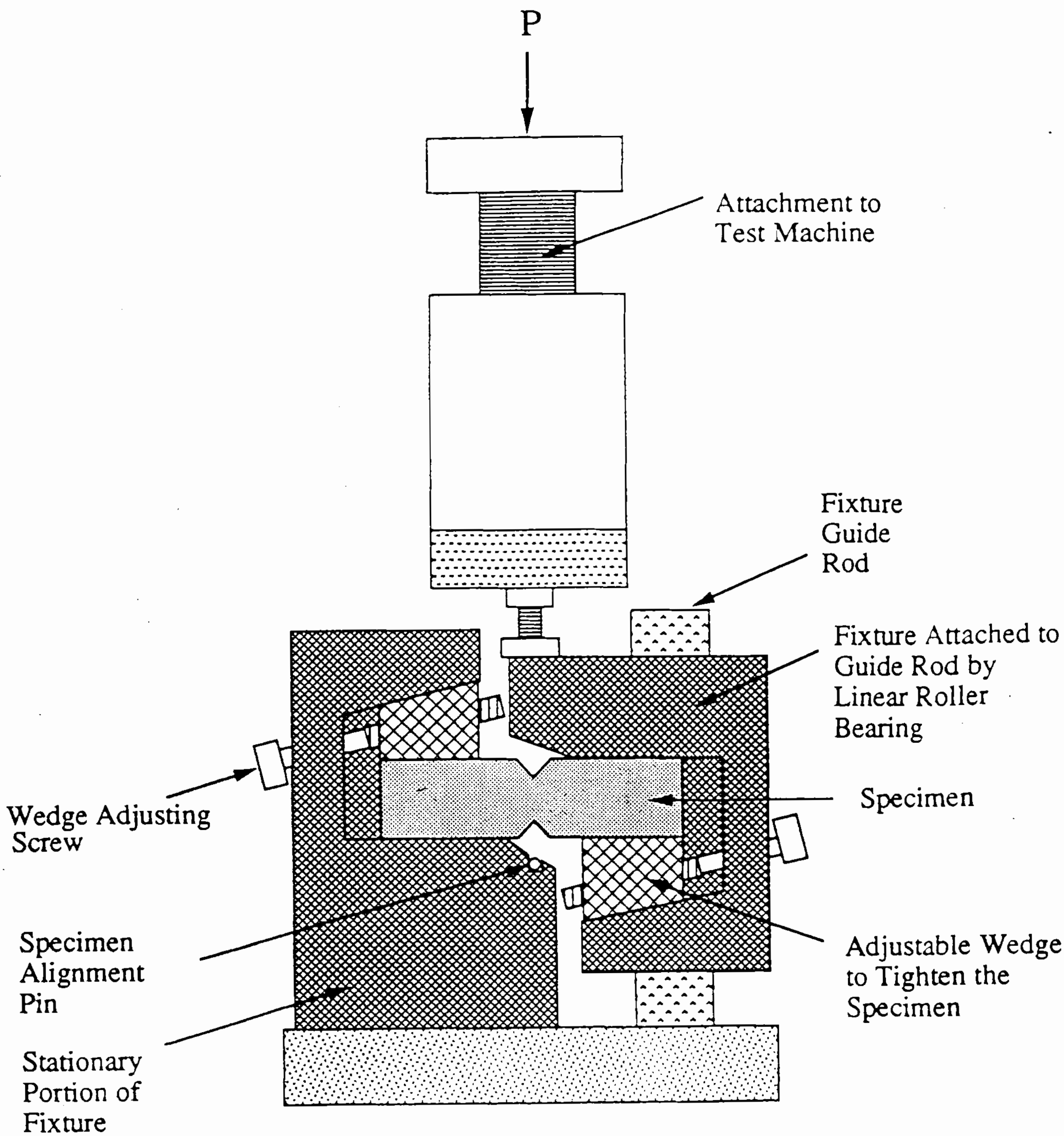


Figure 16. Modified Wyoming Iosipescu Test Fixture [28], Reprinted with Permission

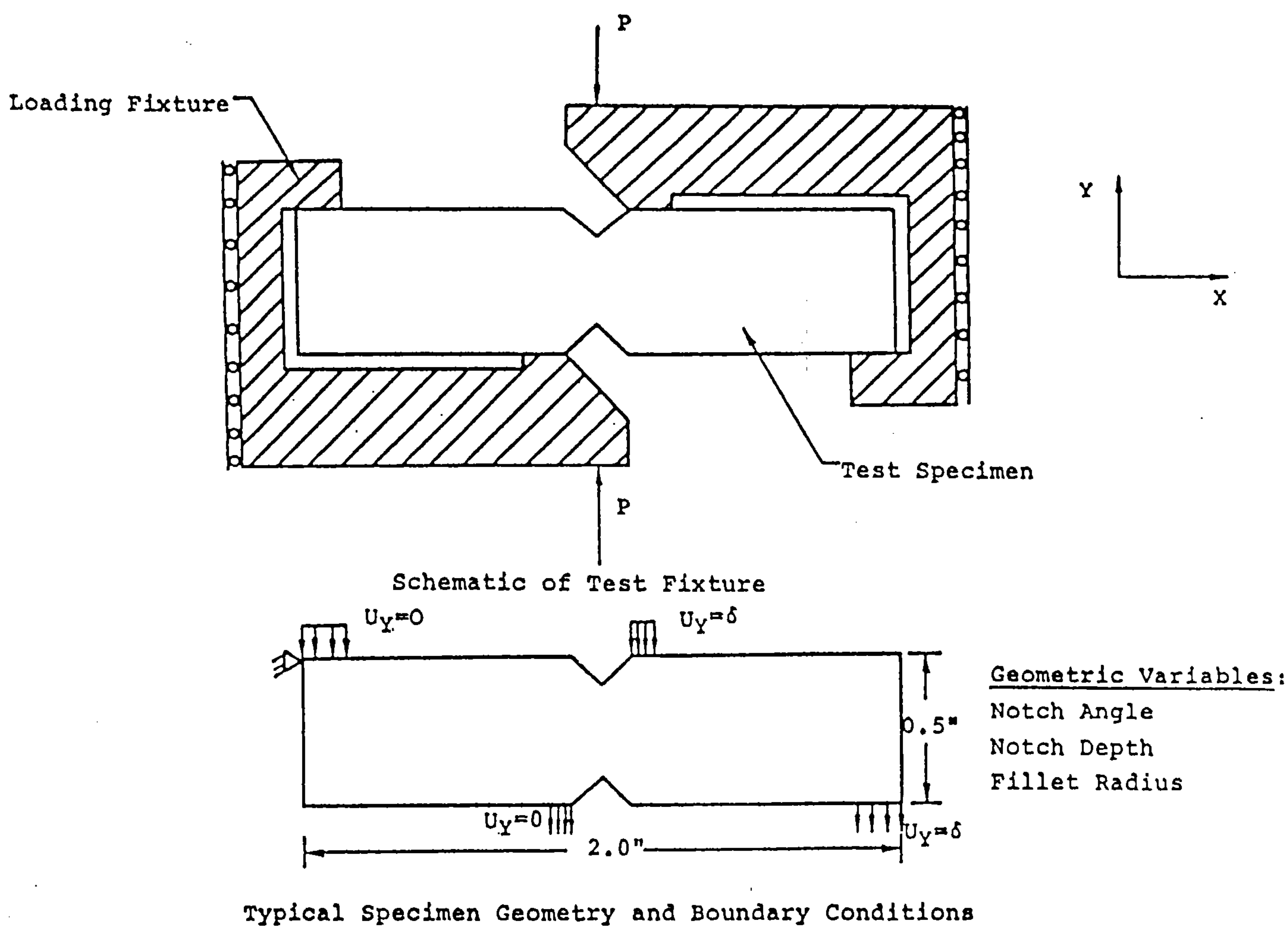


Figure 17. The Iosipescu Shear Test Method [11]

It may be noted that the fixture and the test described above have also been used for determining interlaminar shear response. Bonding of several layers are, however, required to obtain specimens of required size (Figure 18).

3.5.2 Stress States and Failure Modes

Although the stress state was found to be ideal for isotropic materials [24] (it may be noted that the stress state is very good in crossply laminates [11]), a very complex state of stress exists in 0° unidirectional specimens. The stresses (normalized with average shear stress) in a 2" x 0.5" specimen with a sharp 90° notch are shown in Figure 19, which indicates that the stresses are nonuniform even in the test section. Shear stresses are fairly nonuniform and low ($\approx$ 0.8). Transverse stresses are fairly high near the notches and load application points. A marked improvement occurs by introducing a rounded notch (.05" radius). Shear stresses become closer to unity and the transverse stresses are reduced by a factor of 2. Further improvement is noticed when the larger specimen (3" x 0.75") with a 120° rounded notched is used. The shear stress in the test section becomes of the order of 0.93 times the average shear stress (Figure 20) and transverse stresses are reduced further because the load application points are moved away from the test section.

Even with the introduction of the rounded notch, damage initiates at the notch roots [8] causing splitting in 0° specimens (Figure 21) and the load drops at this point. The load can be increased, however, and the final failure load is attained after the splits become constrained as they progress towards region of lower stresses. A typical pattern of damages in 0° specimen is shown in Figure 22, which indicates the development of more transverse cracks, which are expected due to shear, and can be considered to be representative of what may occur in a laminate or a structural component.

It may be noted that an ideal state of pure shear over a large area (= average stress) does not exist in 0° specimens. A small area ($\approx$ 0.1" x 0.1") in the center can possibly be considered to be in pure shear. A more ideal state exists in 90° specimens [29], but such specimens fail early because of easy fracture path available (parallel to fibers and connecting the notches). Such a failure mode is not representative of shear failure of a lamina in a laminate containing laminae of other orientations.

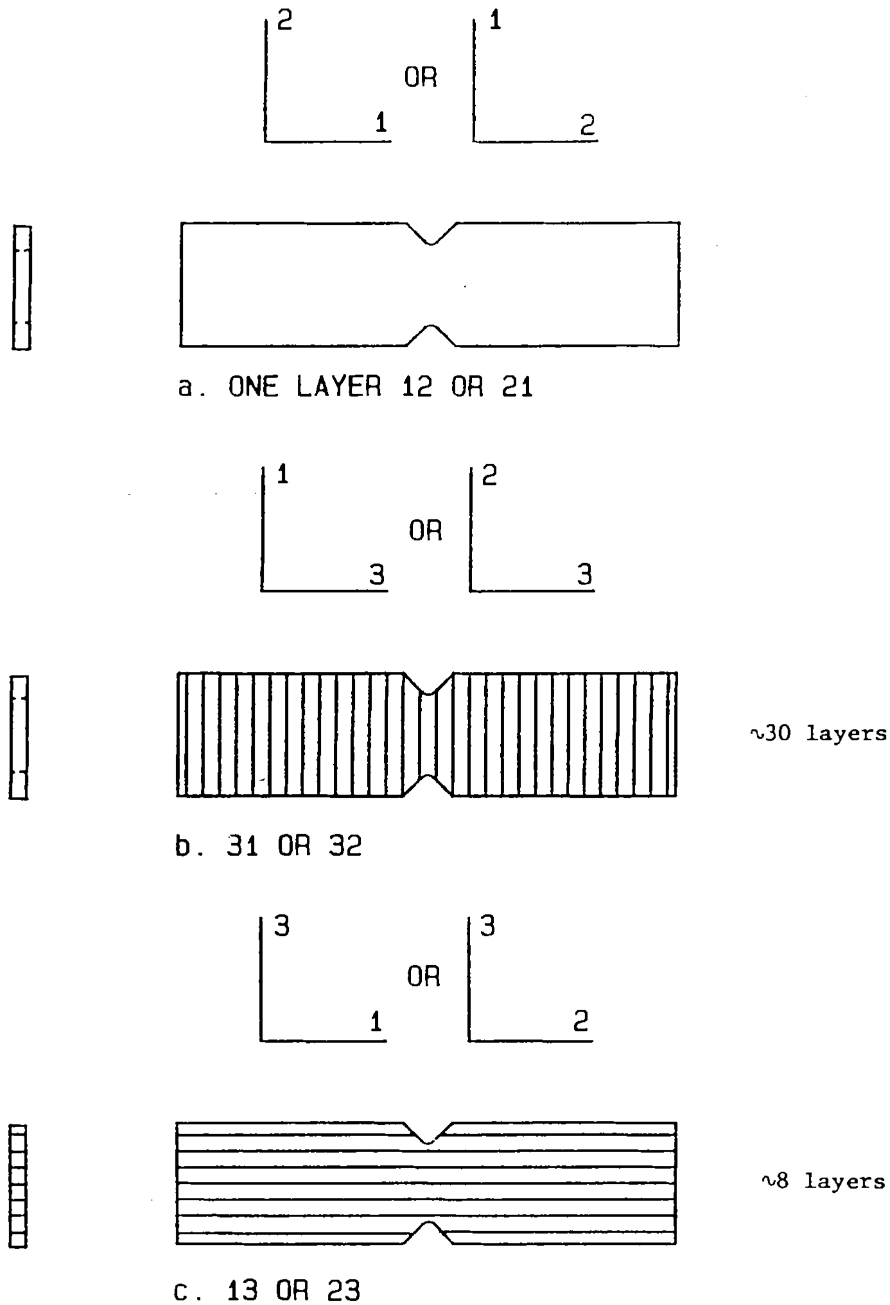


Figure 18. Iosipescu Shear Test Specimen Configurations [25]. Reprinted with Permission.

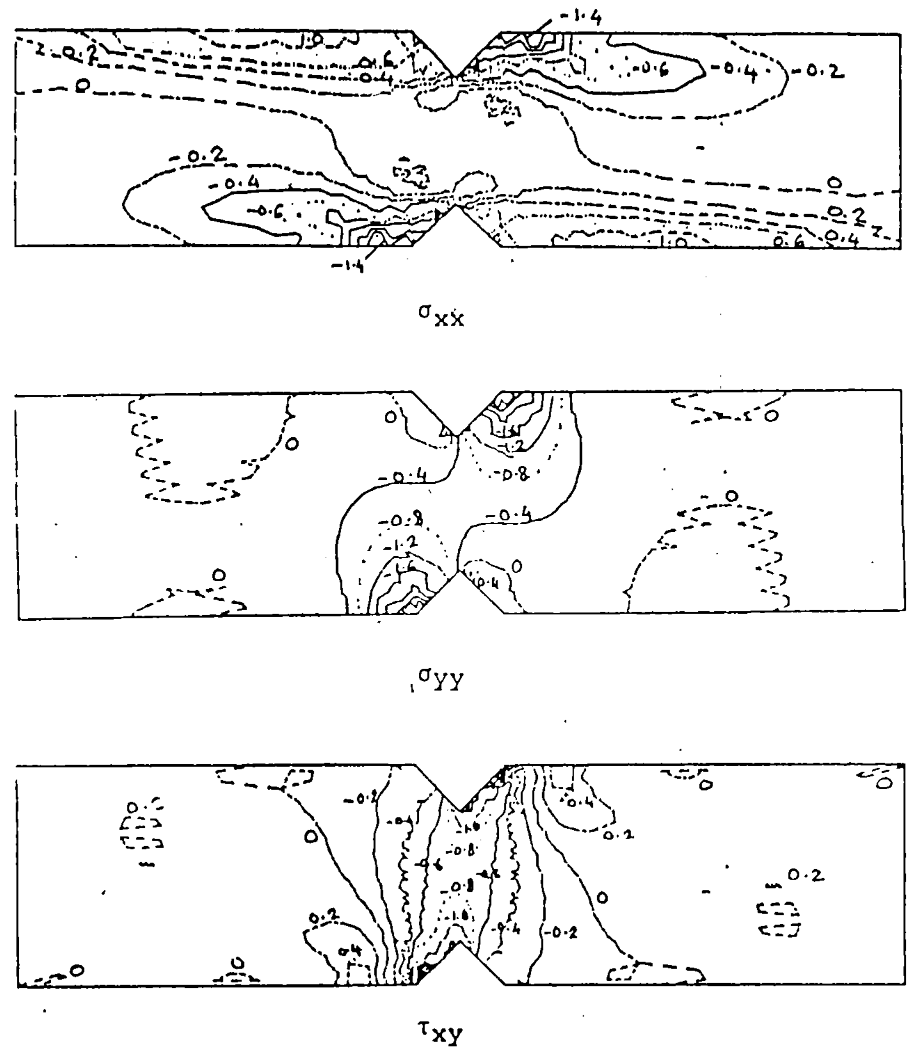


Figure 19. Stress Contours in an Iosipescu Specimen with Baseline Geometry for 0° T-300/Epoxy [11]

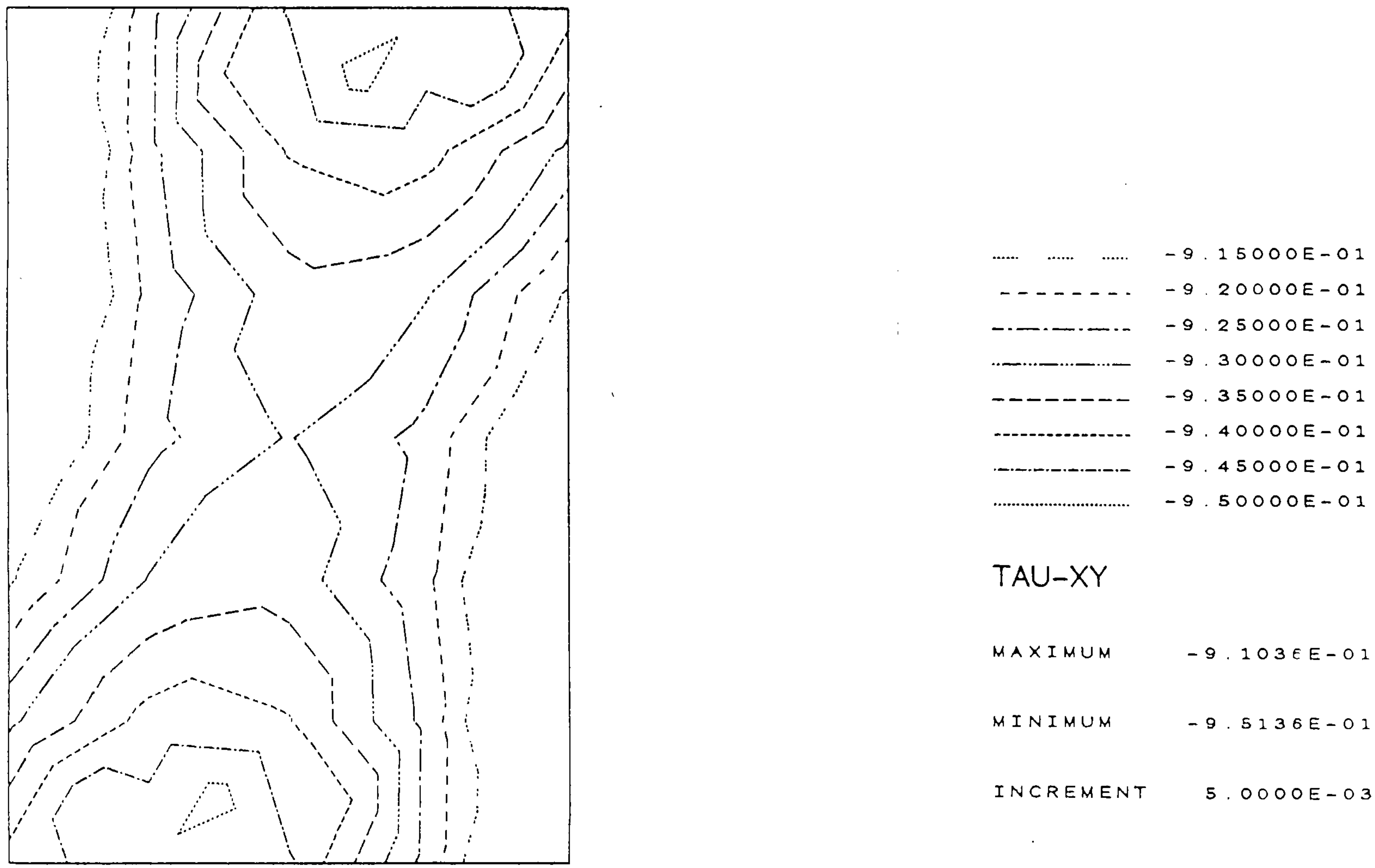


Figure 20. Normalized Gage-Section Shear Stresses in 3 in. x 0.75 in. 120° Rounded Notch Iosipescu Specimen, 0° T-300/Epoxy [11]

Figure 21. Typical Axial Splitting at Notch Tip in Iosipescu Specimen, Reprinted from [8] by Permission of the Publishers, Butterworth Heinemann Ltd ©

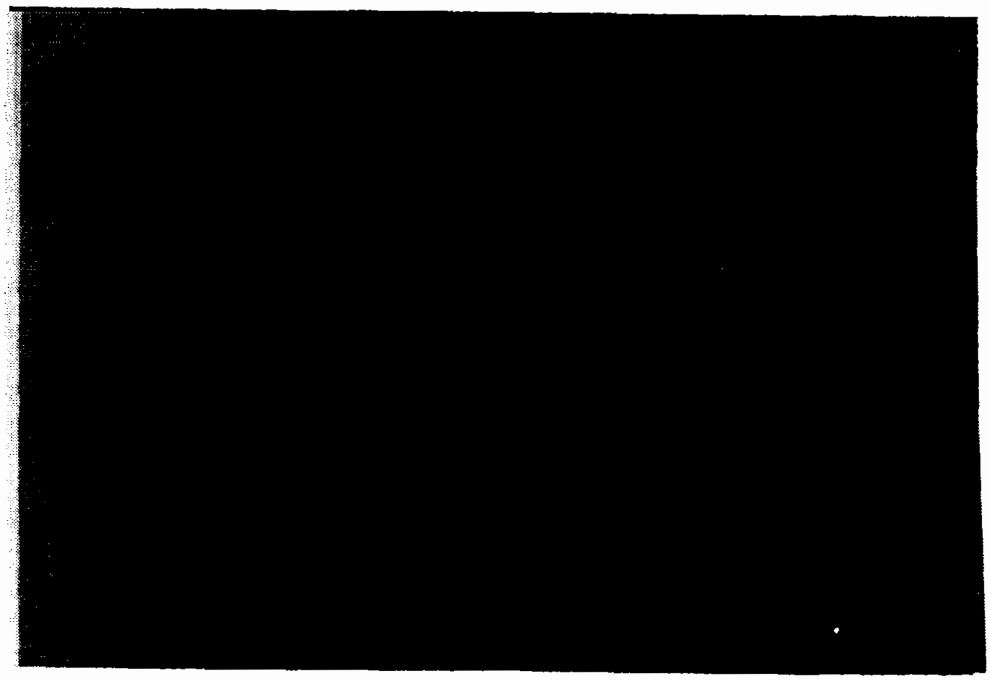


Figure 22. Dye-Enhanced X-Radiograph of a Failed Iosipescu Shear Specimen of $[0]_{8T}$ AS4/3501-6 Graphite/Epoxy Composite, 110-Degree Notch Configuration, Courtesy: D.F. Adams, University of Wyoming

As mentioned earlier, crossply specimens yield better stress distributions and more realistic failure modes, showing more distributed microcracking in the layers. Stress distribution in quasi-isotropic layups is also good but that in the ($\pm 45°$) layup is worse. Factors are needed for correct evaluation of shear stress, which is nominally defined as load per unit area of the test section (see [11]). Shear strengths of quasi-isotropic and ($\pm 45°$) layups are high, and serious problems arise in testing thicker specimens. On the other hand, thinner ($\pm 45°$) specimens need tabs [11] to avoid local failure near loading points. Thin unidirectional specimens may also need the use of tabs when used in the original APFB type fixture [29]. Fiberglass tabs (0.075" thick) on the loading edges (and also on sides) have been used and are not found to have strong influence on the results.

Considerable inconsistency in data has been observed by various investigators using the Iosipescu specimen. With improvements in the fixture and good loading arrangements, the test has been considered for an ASTM Standard. Round robin results have been found to be acceptable and a standard has been approved by the D-30 Committee.

3.5.3 Data Reduction

Strains should be measured with three-element rosettes (or two 45° gages). Back-to-back gages may be required if there is a chance of bending, which sometimes do occur. Shear stress is taken as the average value in the notched section (load/area). However, as noted earlier, stress states in 0° specimen are not uniform and a correction factor is required, i.e., 0.84 and 0.93 for 90° and 120° notch, respectively, as obtained from elastic finite element analyses. After the notch tip damage initiation and onset of inelastic strains, the stress state becomes more uniform. Therefore, there is a dilemma in using a constant correction factor over the entire stress-strain history.

3.5.4 Other Requirements and Modifications

Monitoring the output from tensile and compressive (two 45° gages) strain gages have been suggested [30] as a means of checking for pure shear. However, this factor is not as important as bending and twisting effects [28]. Placing the specimen into the fixture should be done in a careful manner, and the loading faces should be ground smooth and parallel to avoid inplane or out-of-plane bending or twisting. Soft shim materials can reduce these effects [30]. Good quality notches are needed, and these can be machined with proper care [30].

A modified version of this specimen (compact in size) has been suggested for testing specimens from filament wound cylinders [31]. The fixtures are bonded to the specimen with adhesives. It is not clear how this load transfer mechanism will work if high loads are required.

3.6 ARCAN

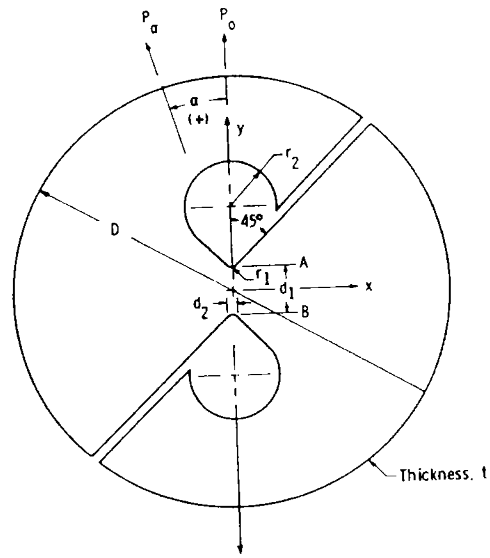
3.6.1 General Description of the Test Method

A biaxial stress test specimen proposed in [32] has been used by some investigators for determining the shear properties of composites. The specimen is in the form of a circular plate with two cutouts as shown in Figure 23 (reprinted from [2]). Application of a vertical load ($\alpha = 0°$) produces a state of shear stress in the central notched portion which is similar in shape to the test section of the Iosipescu specimen. Load applied at an angle to the vertical axis (y) causes generation of extensional stress in addition to shear and, therefore, this specimen can be used for biaxial loading as well as pure shear. Typical specimen dimensions are given in Figure 23.

3.6.2 Stress States and Failure Modes

Shear stress states in the specimen are shown in Figure 24 for unidirectional graphite/epoxy (fibers parallel to y-axis, see Figure 23) and glass/epoxy fabric composites [2]. It is clear that stress gradient is high in the x-direction even within the small distance d_2 (0.11"), which is assumed as the equivalent width of the gage section [2].

Failure often occurs away from the gage section [2] because of complex stress states slightly away from this area. Reinforcements are needed to prevent such failures and it has been suggested [33] that except for a small test area near the notched section, the rest of the specimen be replaced by an aluminum plate bonded to the test material (Figure 25). Stress distribution in such a specimen has not been analyzed in detail but a similar set up has been



D = 5.5"
d_1 = 0.61"
d_2 = 0.11"
r_1 = 0.078"
r_2 = 0.55"

Figure 23. ARCAN Test Specimen as Used in [2]. Copyright ASTM. Reprinted with Permission.

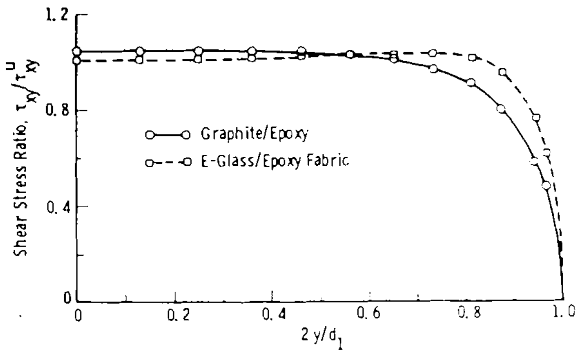
studied in [27]. It may be noted that failure in the unidirectional material with fibers running in the y direction reported in [2] is similar to the 90° Iosipescu specimen (discussed in the previous section), but the failure location is slightly away from the test section. No database exists to research any conclusion about consistency of results or failure modes. The failure mode discussed above is not acceptable.

3.6.3 Data Reduction

Shear strains are measured by strain gages and the shear stress is taken as the load divided by the area of the notched section.

3.6.4 Other Requirements and Modifications

Machining the specimen is a complex task. Modification of the specimen by bonding a small test section to an aluminum plate as discussed earlier may reduce the work, but it is not



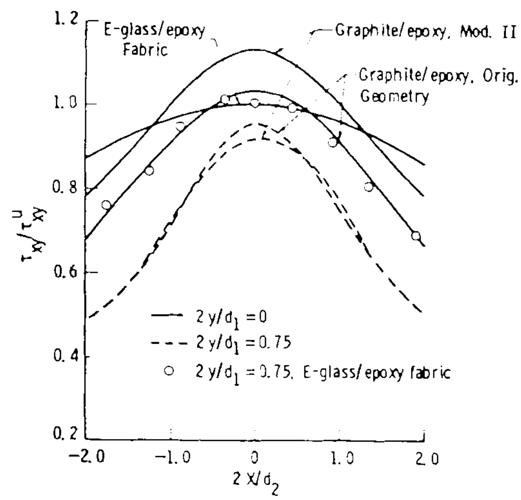


Figure 24. Shear Stress Distribution in ARCAN Specimens in x and y Directions [2]. Copyright ASTM. Reprinted with Permission.

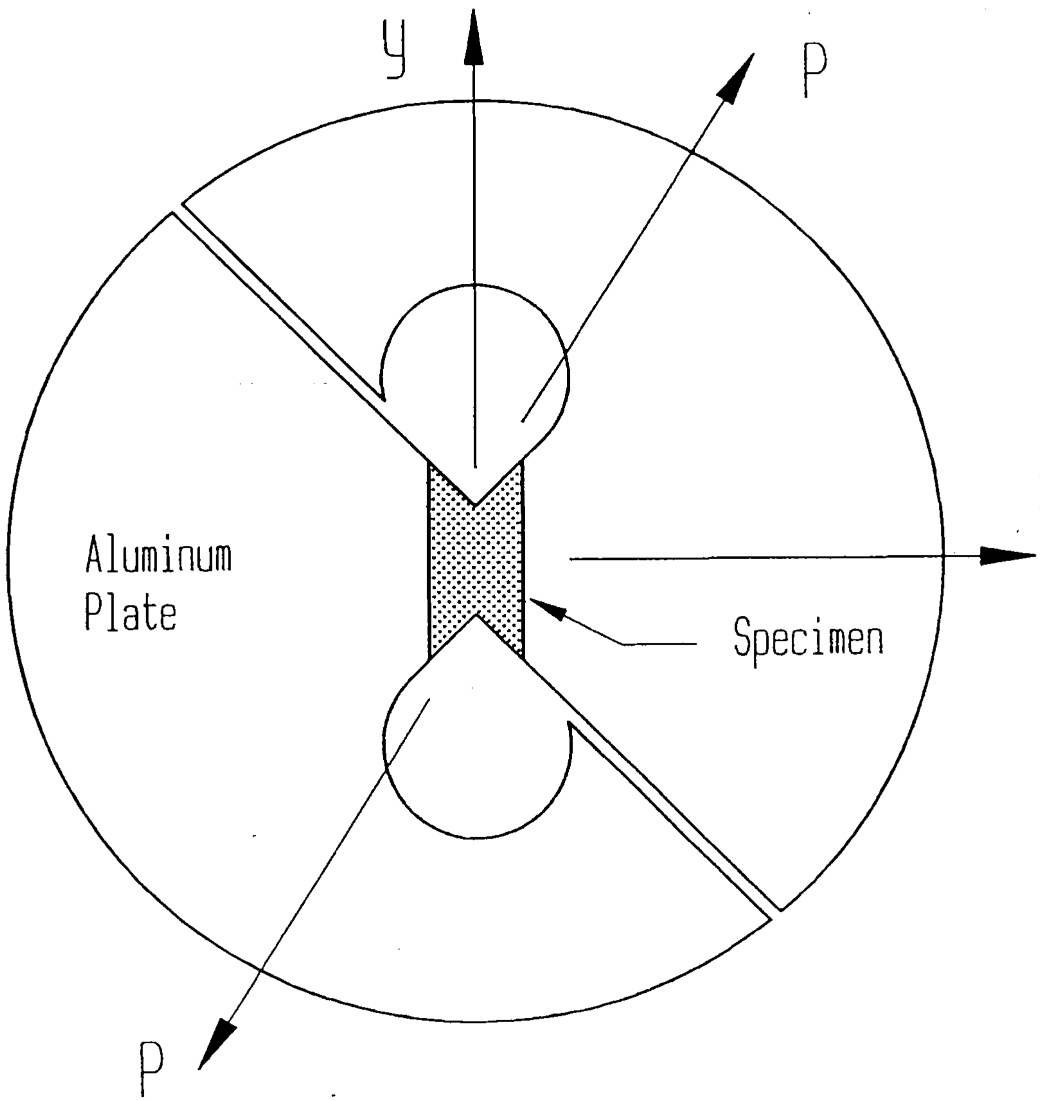


Figure 25. Suggested Variation of the ARCAN Specimen [33]

clear whether such bonding will be able to take high load levels which may be required if fibers run perpendicular to y-axis.

3.7 RAIL SHEAR

3.7.1 Description of the Test Method

Two- and three-rail shear tests have been studied by various investigators. Tests with constant thickness rails bolted to the specimen are described in an ASTM guideline D4255 [34]. A typical three-rail shear fixture with a specimen is shown in Figure 26. Compressive load which is applied in this fixture is commonly preferred over tensile load. Appropriate torque is applied to the bolts to avoid slipping as load is increased. Smaller specimen size is needed when a two-rail fixture is employed. The ASTM guide suggests a bolted two-rail fixture which may be loaded in tension or compression. Various methods have been suggested (such as the use of abrasive paper, soft metal shims, tabs in rail areas, machining grooves or random punching in the rails) to facilitate gripping. Even with the use of such methods, bolt tightening may be needed with increasing load, especially when tension loads are used. For this reason bonding the rails to the specimen (or sometimes in combination with some bolts) has been suggested [35, 36]. The specimens for a two-rail shear test are typically 2.75" x 4 to 6" long in size bonded to steel rails, each 1.125" wide, leaving a test section 0.5" wide between the rails. Constant thickness and tapered rails (thickness varying from 0.75" at loaded end to 0.0625" at the free end, Figure 27) have been employed. A diagonally loaded fixture (as shown in the figure on the left hand side) but with compressive load is usually preferred.

3.7.2 Stress States and Failure Modes

The stress state (normalized with respect to the average shear stress) in a 6" long unidirectional specimen under tensile load with constant thickness rails (fibers running parallel to rails) is shown in Figure 28 [11] for applied tensile load on the fixture. It may be seen that the shear stress is uniform over a large area in the center of the specimen. Some axial stresses (σ_{xx}, x and y axes are shown in Figure 27) do exist in the gage section. Axial,

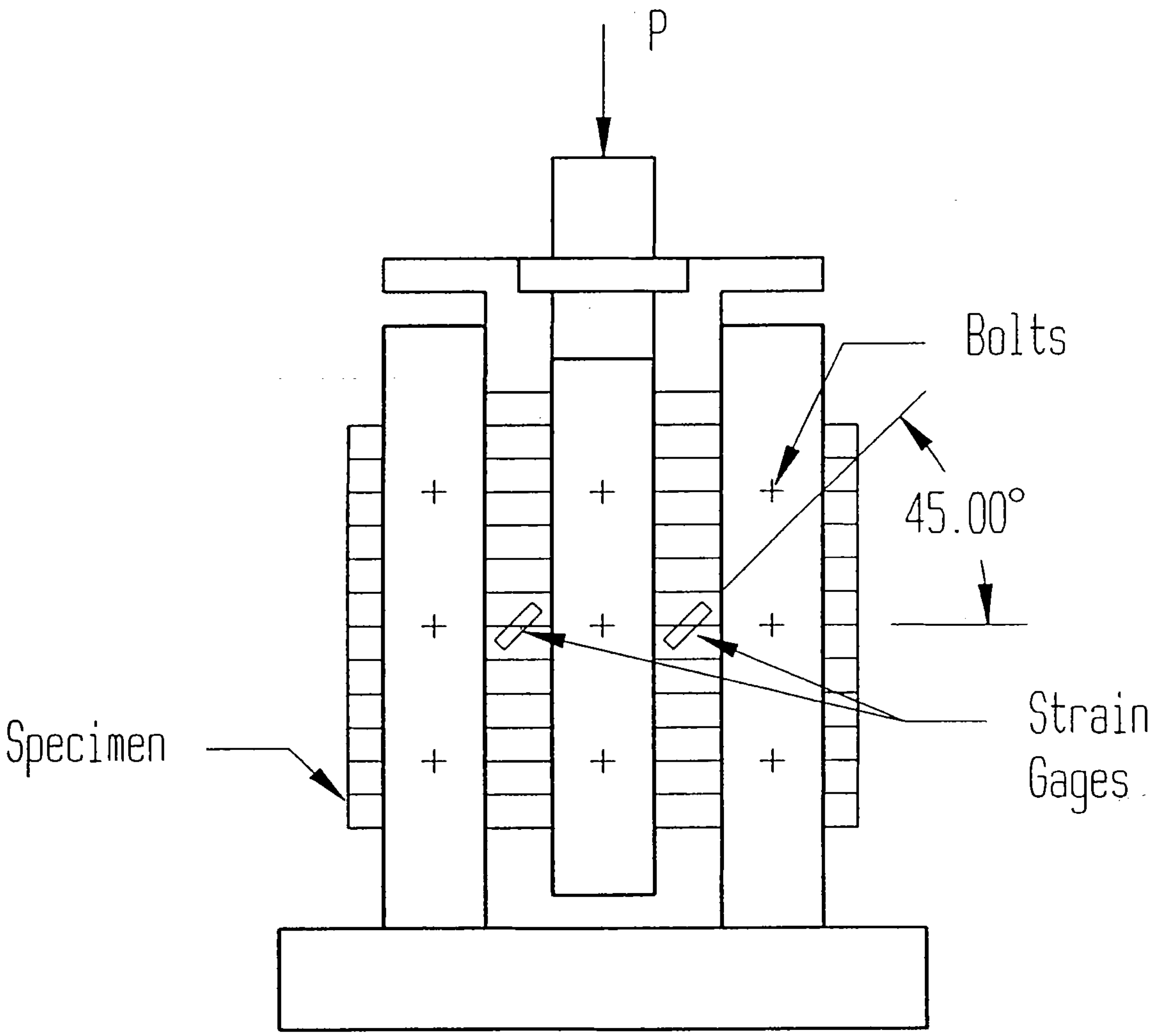


Figure 26. A Schematic Drawing of the Three-Rail Shear Fixture

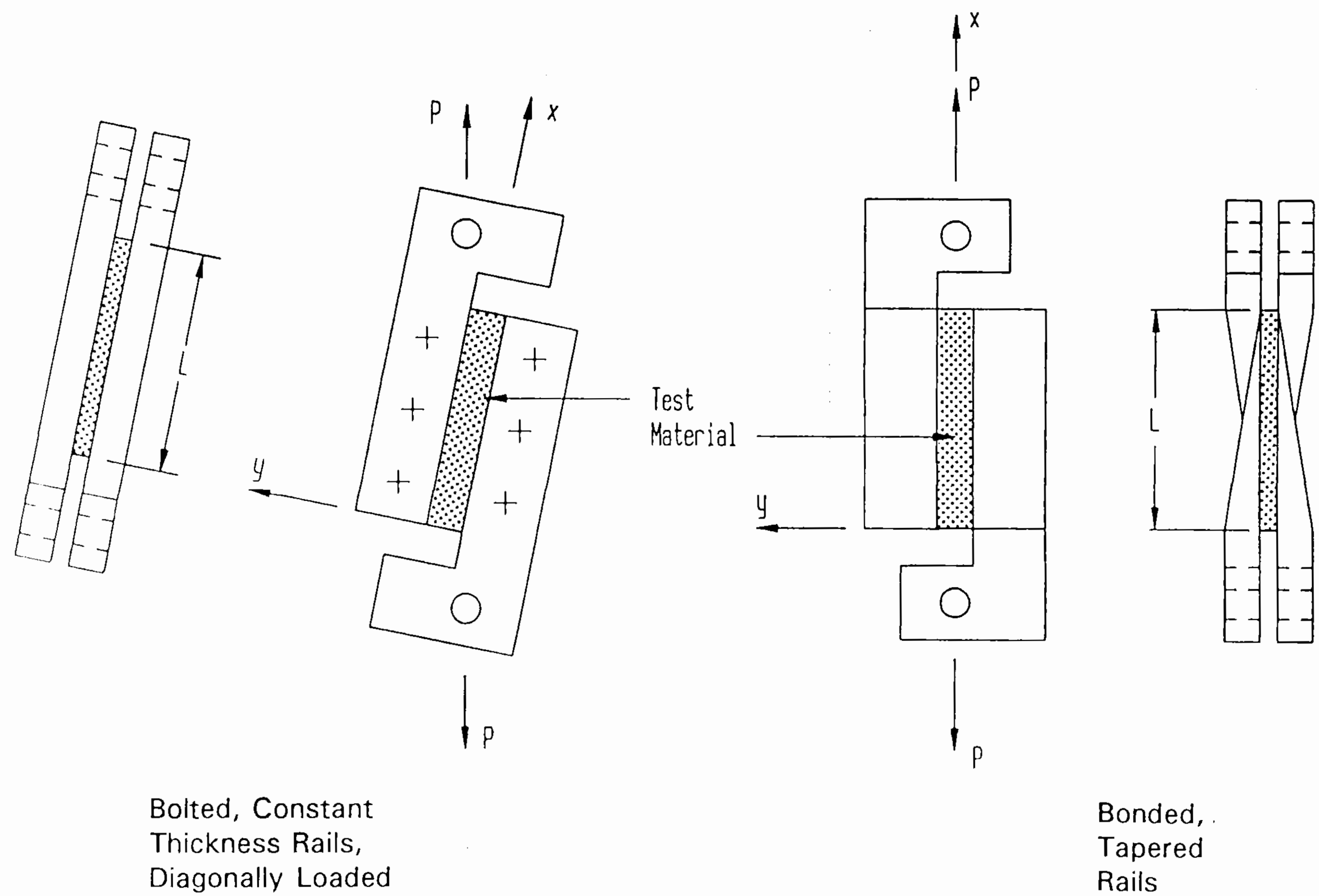


Figure 27. Schematic Drawing of Two-Rail Shear Configurations

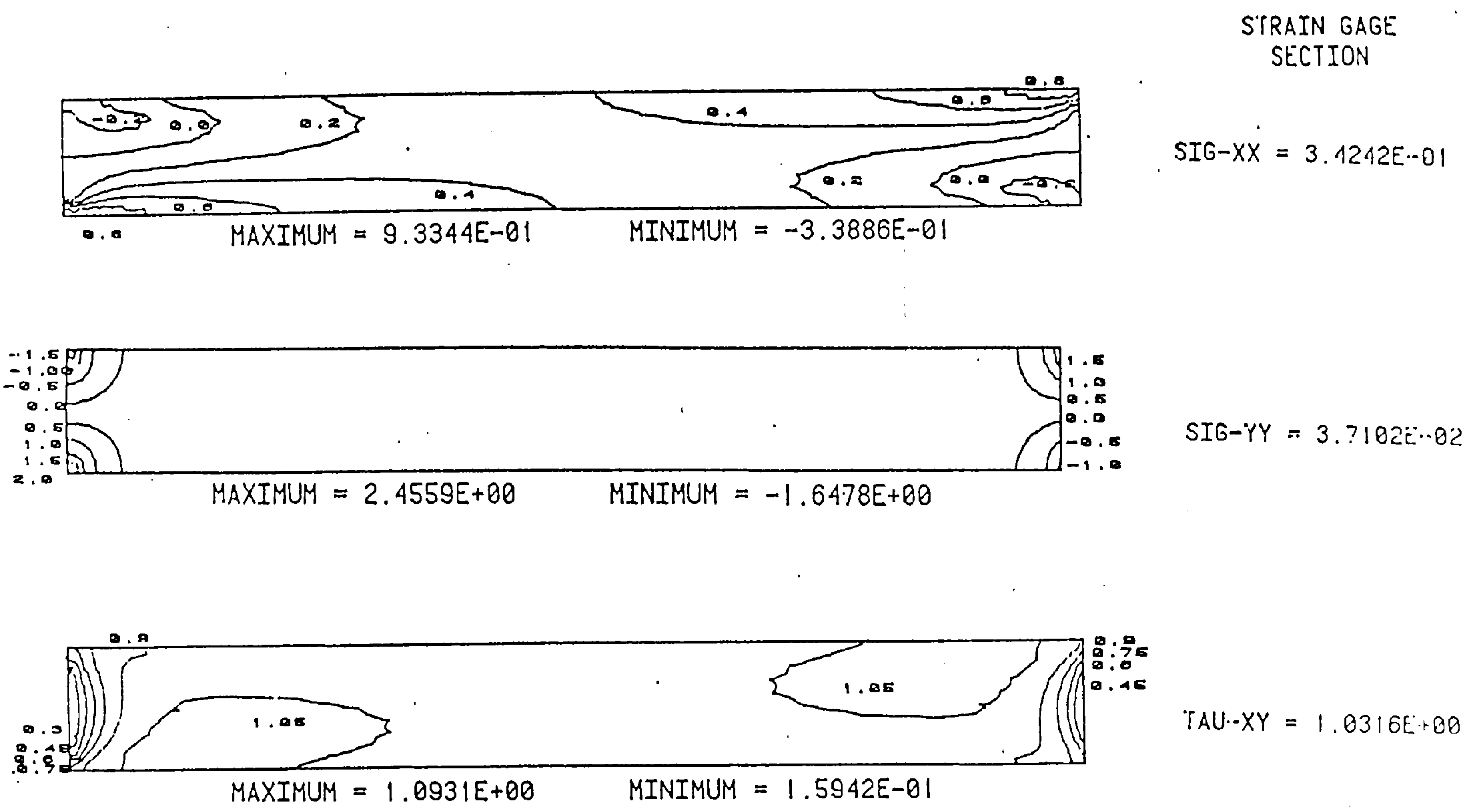
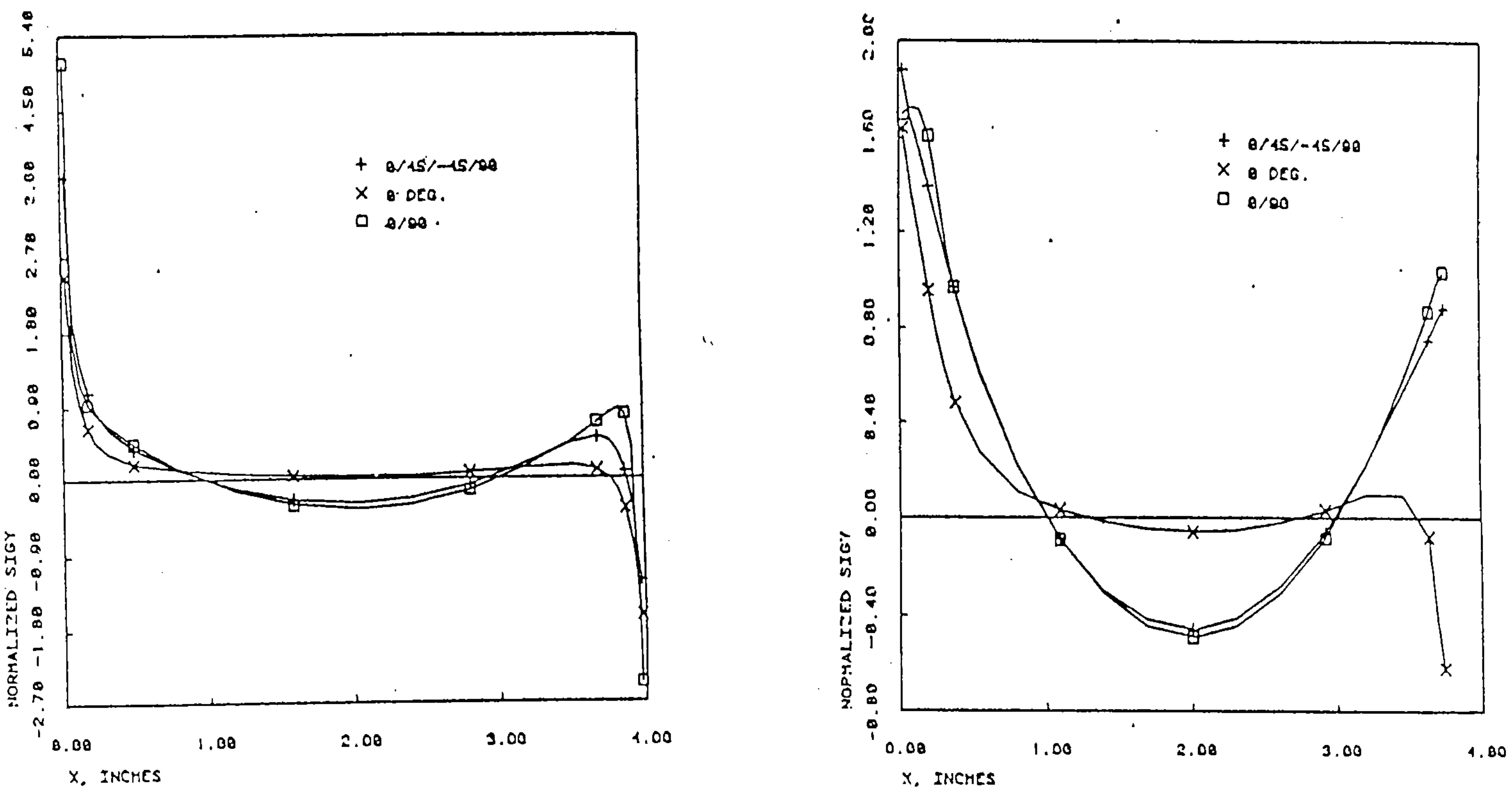


Figure 28. Stress Contour Plots for 0° T-300/Epoxy Rail Shear Test Specimens, 6" Long, Constant Thickness Rails [14], x and y axes are shown in Figure 27

transverse and shear stress are high at all the corners. Stresses in the unloaded corners can be reduced significantly by using tapered rails. The transverse stress (σ_{yy}) variation (along the length) near the rails for three laminates is shown in the figure on the left hand side of Figure 29. It may be seen that the transverse stress remains high near the loaded corner (x=0). It has been suggested [36] that adhesive nonlinearity reduces the stresses near the corners, so that the stress distribution is acceptable. A modification of the specimen in the form of a parallelogram shape (Figure 30) has also been suggested [11, 14] which reduces the stresses to some extent in the loaded corner (Figure 29, parallelogram with $\phi = 60°$). Figure 31 shows that the shear stresses are uniform over a large area and transverse stresses are reduced further.

Failure in unidirectional specimens with fibers parallel to rails occurs in the form of cracks parallel to the fibers which cause large scatter in shear strength [37]. Bolted specimens yield more compliant response than bonded ones [35]. The scatter in strength is reduced if 0.5" long slots (at rail boundaries), which tend to stop unstable crack growth, are introduced at all corners [37]. Tests with fibers perpendicular to rails (or (0/90) laminates) produce failure over a wider zone, with many ply cracks, which appear to be representative of subcritical failures observed in individual plies under shear in a laminate (Figure 32 reprinted from [38]). Representative test data from rectangular ($\phi = 90°$) and parallelogram ($\phi = 45°$) shaped specimens with fibers perpendicular to the rails are compared in Figure 6 with data from other shear specimens [11]. It may be seen that the data from parallelogram specimens compare well with those from Iosipescu specimens. Rectangular shaped specimen data are also acceptable, but the failure strains are a little lower. Data from rectangular and parallelogram shaped specimens for crossply layups have also been found to correlate well with those from Iosipescu specimens [11]. Some of these specimens showed evidence of delaminations (after failure) between plies in addition to individual ply cracks. With compression load, some thin specimens (parallelogram shaped ones in particular) may also show local compressive or buckling failure near the loaded corners [11]. Thicker specimens, on the other hand, may show tensile failure (constrained cracks) at the corners which are not loaded.

Tests have also been performed on thin quasi-isotropic and (±45) layups. Such specimens show signs of delaminations near a corner and compressive crushing in these



Rectangular

Parallelogram

Figure 29. Comparison of Composite Transverse Stresses for Specimen/Rail Interface Elements for Rectangular and Parallelogram Shaped Specimens with Tapered Rails [11]

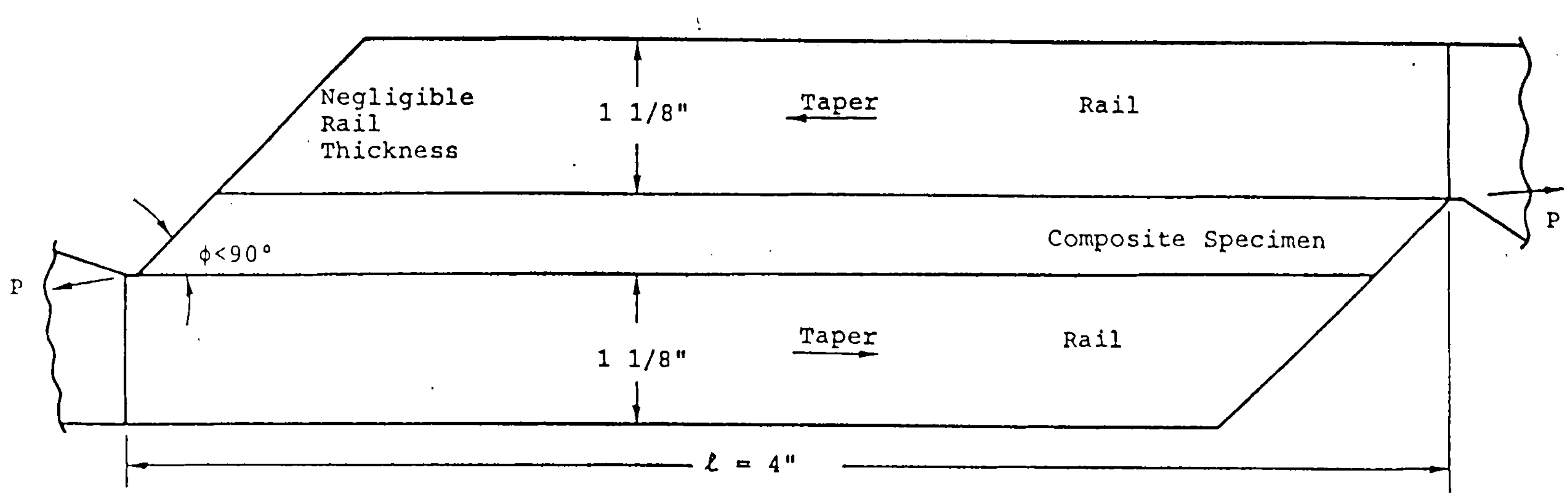


Figure 30. Parallelogram Shaped Rail Shear Specimen with Tapered Rails [11, 14]

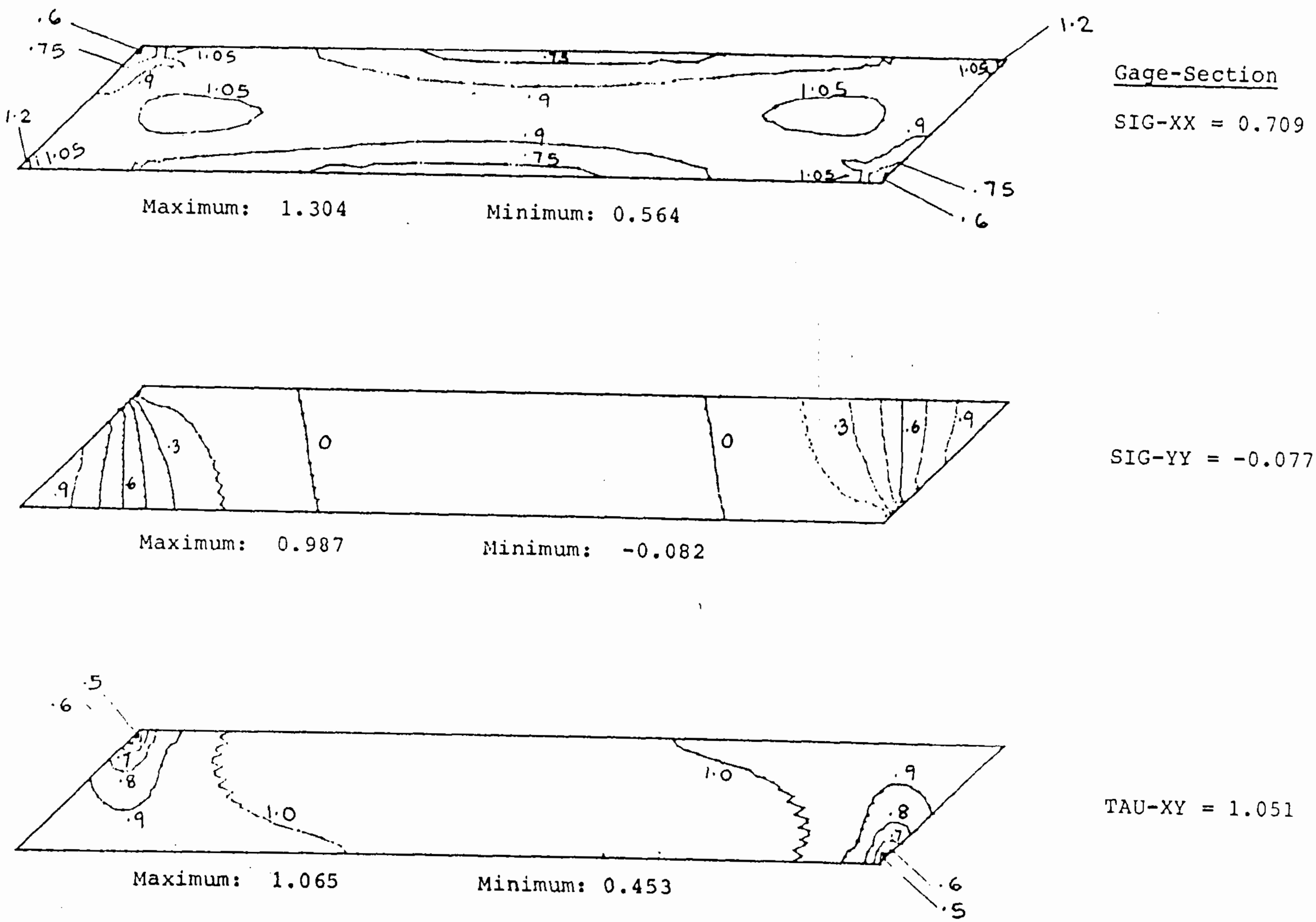
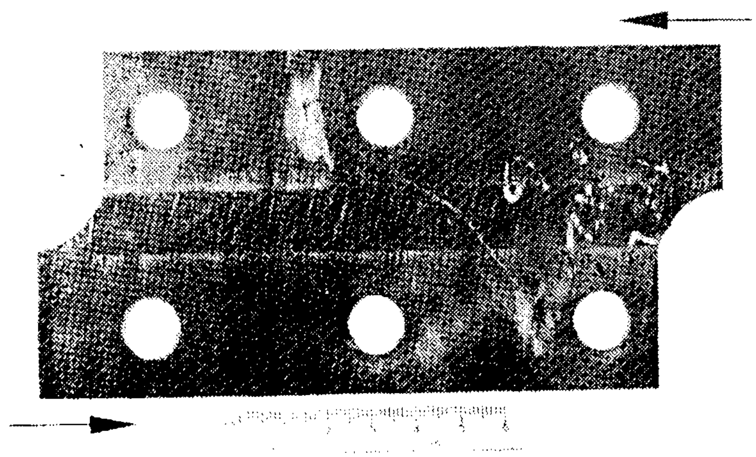
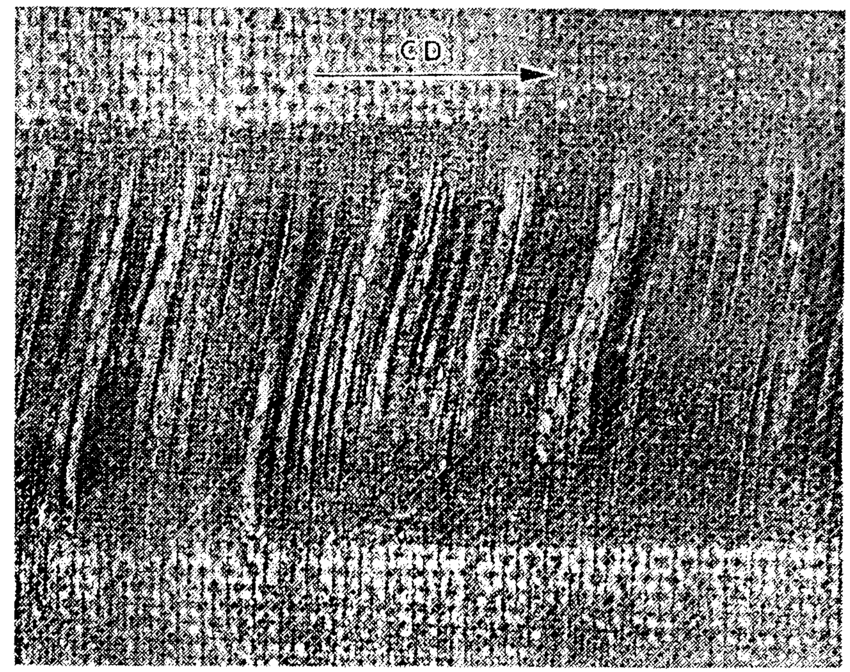


Figure 31. Stress Contour Plots of 0° T-300/Epoxy Parallelogram Shaped Rail Shear Specimen (θ = 45°, L = 4 in.), Tapered Rails [11, 14]. x and y axis are same as those shown in Figure 27.



(a)



(b)

Figure 32. Optical and SEM Photographs of AS4/3501-6 Gr/Ep - $[[0/90]_{6s}$, Inplane Shear-Tested (Baseline) [38]
(a) Macrophotograph of Rail Shear Specimen
Note: Arrows indicate loading direction
(b) Close-Up View of Inplane Shear Region

CD = Crack-propagation direction

locations, possibly due to buckling effects. Testing of thicker specimens, however, may cause bond (or bolt) failures before specimen fracture.

Available data are not sufficient to judge consistency of results from different sources. An ASTM round robin [39] did not yield consistent results. However, new specimen modifications yield a better chance for obtaining consistent data.

3.7.3 Data Reduction

Shear strains are often measured with 45° gages. However, the presence of axial stresses in the test section have been indicated by stress analyses. Therefore, strain rosettes are recommended for calculation of shear strains. The shear stress is evaluated as the load divided by the load bearing area (length of specimen x thickness). However, some correction factors may be needed in ±45 or quasi-isotropic layups since the stress state may show some nonuniformity [11].

3.7.4 Other Requirements and Modifications

No special machining is required other than cutting (and bolt hole drilling if needed). Common adhesives are adequate. High temperature (or hot wet) testing can be a problem because of adhesive failure. Roughening and bolting have been used [35]. Thermal mismatch between rail or specimen will also influence the results at high temperatures.

Some minor misalignments in fiber placement or specimen placement may be tolerated. However, significant fiber misalignments will affect the results.

A modified version of the specimen can be used for measurement of interlaminar shear strength (Lap Shear test). In this modification rails have to be bonded directly on to specimens. A parallelogram shaped specimen (similar to the one discussed earlier) has been used for testing carbon-carbon composites.

3.8 OFF-AXIS TENSION

3.8.1 General Description of the Test Method

Tensile testing of off-axis laminates (Figure 33) with fiber direction making an angle of 10° to 15° to the loading direction produces a significant amount of inplane shear stress. Consequently this specimen was suggested for shear testing [40]. Unfortunately, tensile normal stress perpendicular to fibers also exists and may cause early failure. A typical test specimen is a straight-sided one 0.5 to 1" wide x 10" long with 1 ½" tabbed lengths at each grip. Both straight and tapered tabs have been used. However, direct gripping of the tabbed ends (clamping) creates an undesirable state of stress (in the gage section as well as at the ends) due to shear extension coupling (Figure 33) unless the length-to-width ratio is quite long [41]. For this reason, several attempts have been made in designing suitable tabs and rotating end grips to reduce end effects [42-45] (on measurements of modulus and strength) as discussed later.

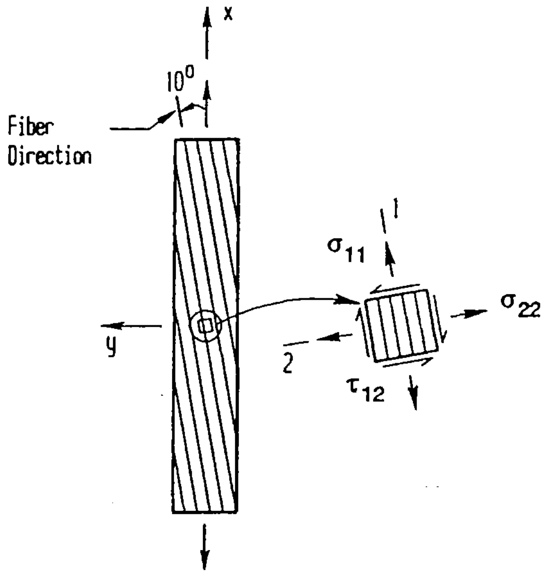
3.8.2 Stress States and Failure Modes

The stress state in the specimen in absence of any end constraints is given by

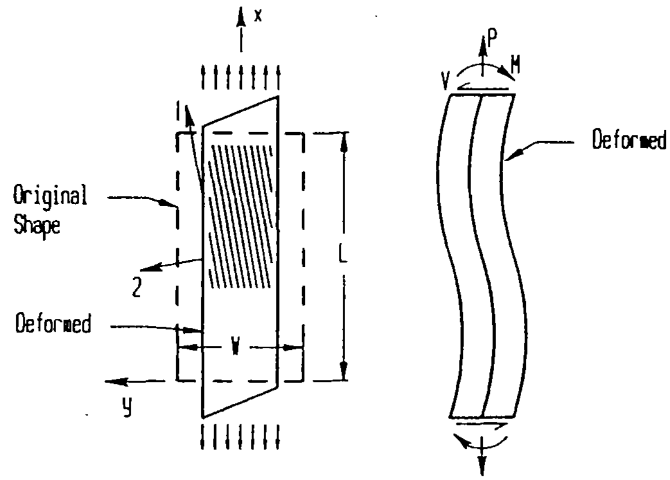
$$\begin{aligned} \sigma_{11} &= \sigma_{xx} \cos^2\theta \\ \sigma_{22} &= \sigma_{xx} \sin^2\theta \\ \tau_{12} &= \sigma_{xx} \sin\theta \cos\theta \end{aligned} \tag{17}$$

However, if the ends are constrained against rotation, the stress state is disturbed by moments and shear forces at the ends (Figure 33). Although, these quantities reduce with increasing L/W ratio, it is imperative that hinged grips (Figure 33) should be used to load the specimen [42, 43, 45]. Even though rotation of the clamp is permitted, the specimen is gripped in the clamp and is not allowed to deform freely. For this reason, the stress state is still not ideal.

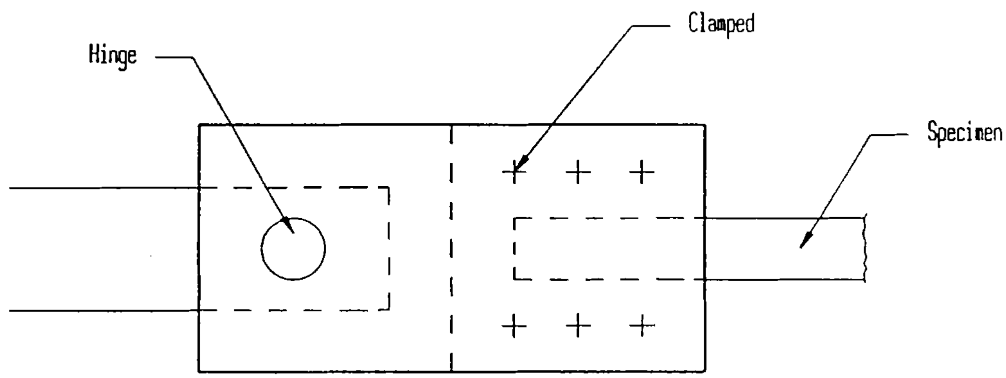
Attempts have also been made to improve the performance of the specimen by changing tab material, inclination of tab ends (not perpendicular to specimen axis, i.e,. not square



Local stresses in specimen originally suggested in [40]



End effects, see [43]



Hinged grip fixture [42,43,45]

Figure 33. Off-Axis Specimen, End Effects and Hinged Grip Fixture

ended), tapered tabs and fiber alignment of tab materials. It has been found that for a given material system and chosen off-axis angle θ, it is possible to design the tabs to reduce constraint effects [42]. However, due to data scatter observed in tests (which occur due to fiber misalignments), the beneficial effects are not confirmed by test data. The off-axis angle itself can be chosen to maximize shear stress or minimize transverse tensile stress (not simultaneously). It appears that off-axis angles between 10 and 15 degrees and fiber glass cloth tabs with one reinforcement direction parallel to fiber direction in the specimen are appropriate.

It has been shown [43] that correction factors are required to calculate the correct shear stress, which is less than that given by equation (17) due to end constraint. For common graphite/epoxy composites these factors are close to unity for $\theta = 30°$. For $\theta = 10°$, it varies from 0.87 (L/W = 10) to 0.96 (L/W = 20). For $\theta = 15°$, the values are 0.95 and 0.98, respectively.

As discussed earlier, even with the various modifications suggested, failure of off-axis graphite/epoxy specimens occur at very low shear strain levels (slightly higher than the strain at onset of nonlinearity) due to a combination of transverse tension and shear stresses. A straight crack develops early and separates the specimen in two pieces. Some materials may perform slightly better, but it is unlikely to yield the desired failure in the form of many constrained ply cracks and significant nonlinear response beyond the onset of initial damage.

With appropriate correction factors, the test method is found to yield reliable values of modulus [11, 43]. Inconsistencies have been reported in previous studies because of the use of low L/W ratios without appropriate correction factors.

Suitable adhesives are needed for bonding tabs for hot/wet testing. Testing without tabs may also be attempted.

3.8.3 Data Reduction

Data reduction involves computation of shear strain from strain rosette data and the correct value of the shear stress (based on elastic theory as discussed earlier).

3.8.4 Other Considerations and Modifications

Although numerous modifications have been suggested to improve the performance of the specimen, it is not likely to yield the nonlinear shear stress-strain response for brittle matrix composites. It may perform well for composites which show some ductility in the transverse direction.

There are no special machining requirements and the specimen preparation is simple. The results, however, can be influenced by fiber misalignment and the effects can be evaluated by using equation (17). Some of these effects have been studied analytically and experimentally [42].

3.9 PICTURE FRAME SHEAR

3.9.1 General Description of the Test Method

In the picture frame shear test, the specimen is bonded or bolted to a stiff four bar linkage system (without or with tabs or doublers). The specimen may be a laminated plate (for small panels) or two parallel plates bonded to a honeycomb (for 4" x 4" or larger panels) to avoid buckling in the specimen (Figure 34 [46]). A tensile load is applied (vertically as shown in the figure), which also causes a horizontal compressive force because of the linkage system. As a result, a state of shear (at 45° to loading directions) is created in the test specimen (Figure 34). The test has also been used to investigate buckling and post-buckling behavior of thin plates [47] as well as response of such plates under other biaxial loading [48]. It has been used and modified by several investigators and a few variations and sizes of the fixture have been tried for testing metals as well as $(\pm 45)_{ns}$, $(0/90)_{ns}$ and $(0/45/90/\text{-}45)_{ns}$ composite laminates. Results are not found to be very encouraging.

3.9.2 Stress States and Failure Modes

A photoelastic investigation [49] showed that stress distribution differs substantially from that of pure shear except near the edges where failure usually occurs. Thus the test may yield a measure of shear strength, but not the modulus. However, some investigators

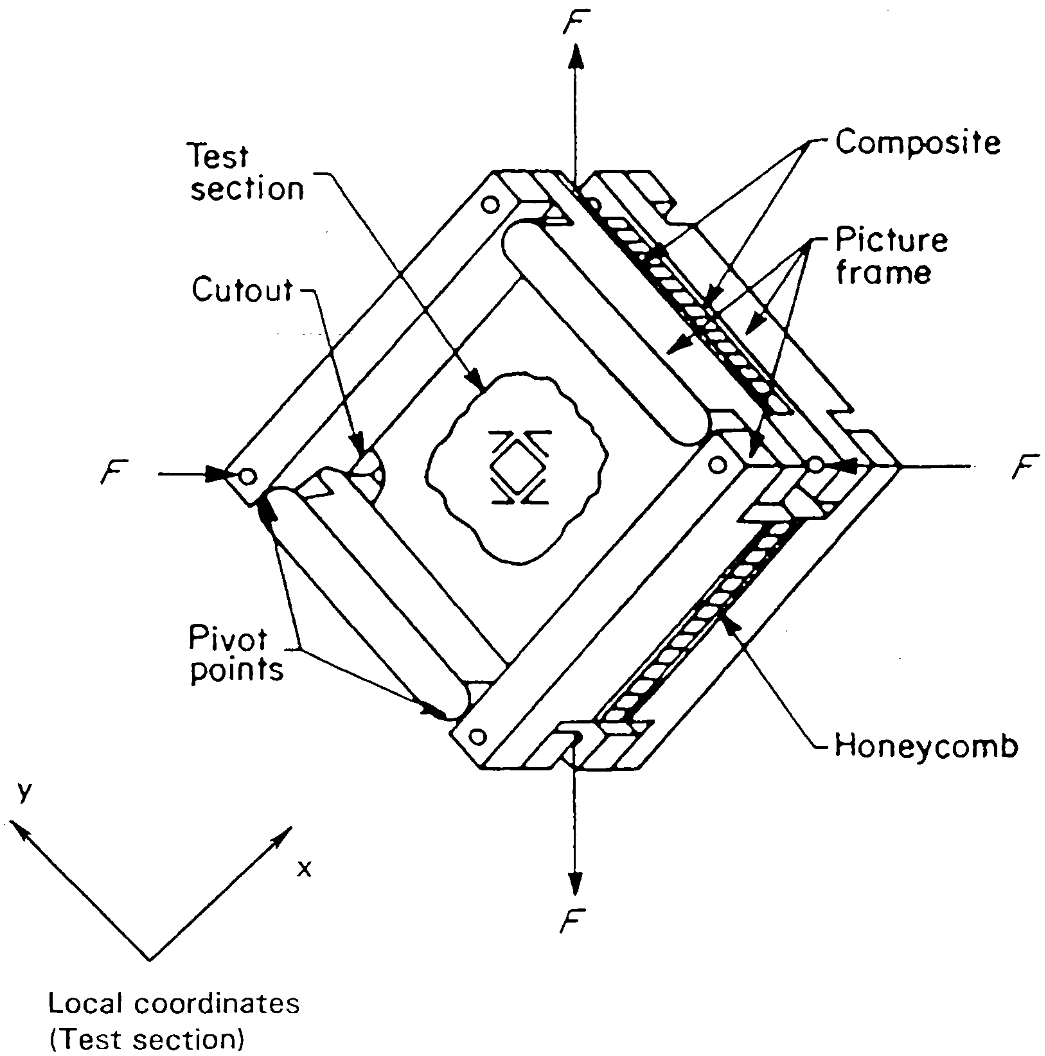


Figure 34. The Picture Frame Shear Test [49], Reprinted from [46] by Permission of the Publishers Butterworth Heinemann, Ltd. ©

[50, 22] reported that good modulus values and stress-strain response can be obtained for $(0/90)_s$ laminates, but the stress-strain data at high strain levels are questionable. Other finite element (including frame and nonlinear effects) and experimental studies on laminate specimens with corner cutouts [51, 52] indicate that stresses are high near the corners. Strengths are found to be low with the use of the sandwich construction. Extensional stresses (σ_{xx}, σ_{yy}) near the corners can be reduced and the stress distribution can be improved by locating the loading corner pins at the corners of the test section (at cutouts made at the intersection of loading tab and test section boundaries, shown in Figure 34) [47]. The ratio of tab (doubler) stiffness to specimen stiffness ($E_d t_d / E_s t_s$) is found to have a strong influence on the shear stress gradient near the corners (Figure 35) and a high value of this ratio (≥ 30) is needed for aluminum panels [47]. If the effect of compliant adhesive is considered, the situation worsens and higher values of this ratio (≥ 50) are needed to reduce the extensional stresses near the corners and create a more uniform shear stress distribution. Some results for $(0/45/90/-45)_{ns}$ laminates are shown in Figure 36 [53].

High stiffnesses of doublers, however, are difficult to achieve and for this reason, measured modulus values are usually low. Failures originate at the corners in the form of broken fibers, but significant amount of splitting is noticed [53] along the edges (Figure 37) before final failure. Therefore, a measure of shear strength can possibly be obtained as discussed earlier.

Test results obtained so far indicate that it is difficult to obtain consistent and reliable data. Test fixtures and specimen preparation are usually very complicated. Designing a proper fixture for testing of laminates (as opposed to sandwich) constructions which yield reliable data has eluded the investigators [53] because of reasons discussed above. The test has been used for hot/wet testing following ASTM D2719-76 [50], but results at high strains are questionable.

3.9.3 Data Reduction

Data reduction is simple if a state of pure shear is obtained and shear strains are measured in the test section. Stress distribution, however, depends strongly on specimen and fixture stiffnesses and complicated stress analysis is required to determine the correct shear stress.

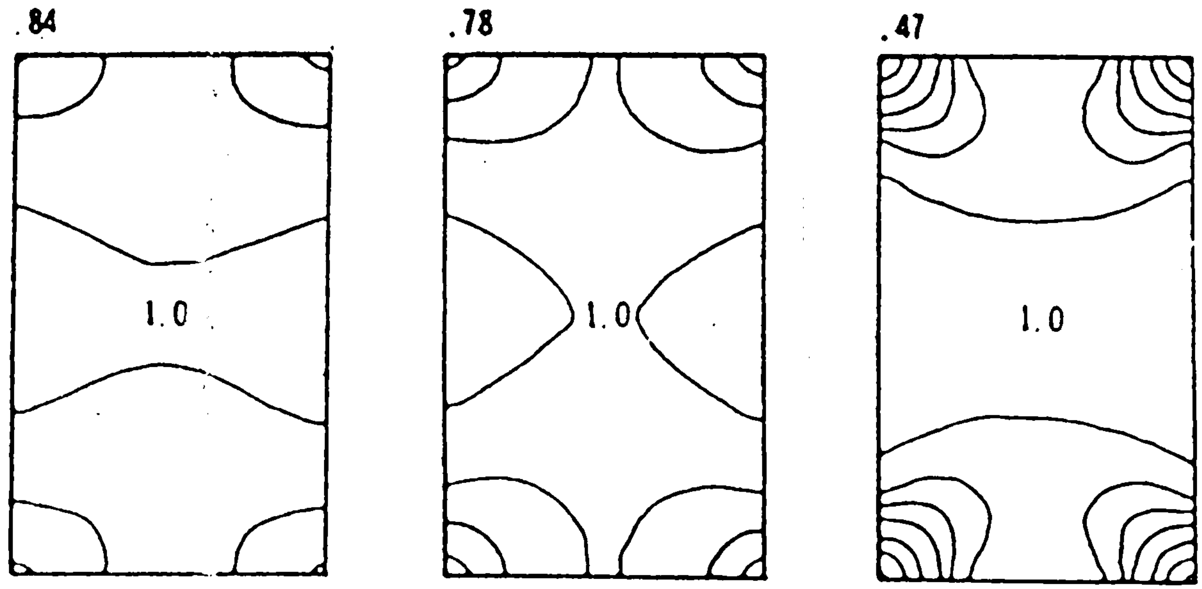


Figure 35. Contours of Normalized Shear Stress (with respect to applied shear) for Varying Ratio of Doubler to Specimen Stiffnesses for a Rectangular Isotropic Panel [47], Courtesy: G.L. Farley, U.S. Army Vehicle Structures Directorate, Hampton, VA.

Left - stiffness ratio = 30
Center - stiffness ratio = 10
Right - stiffness ratio = 1

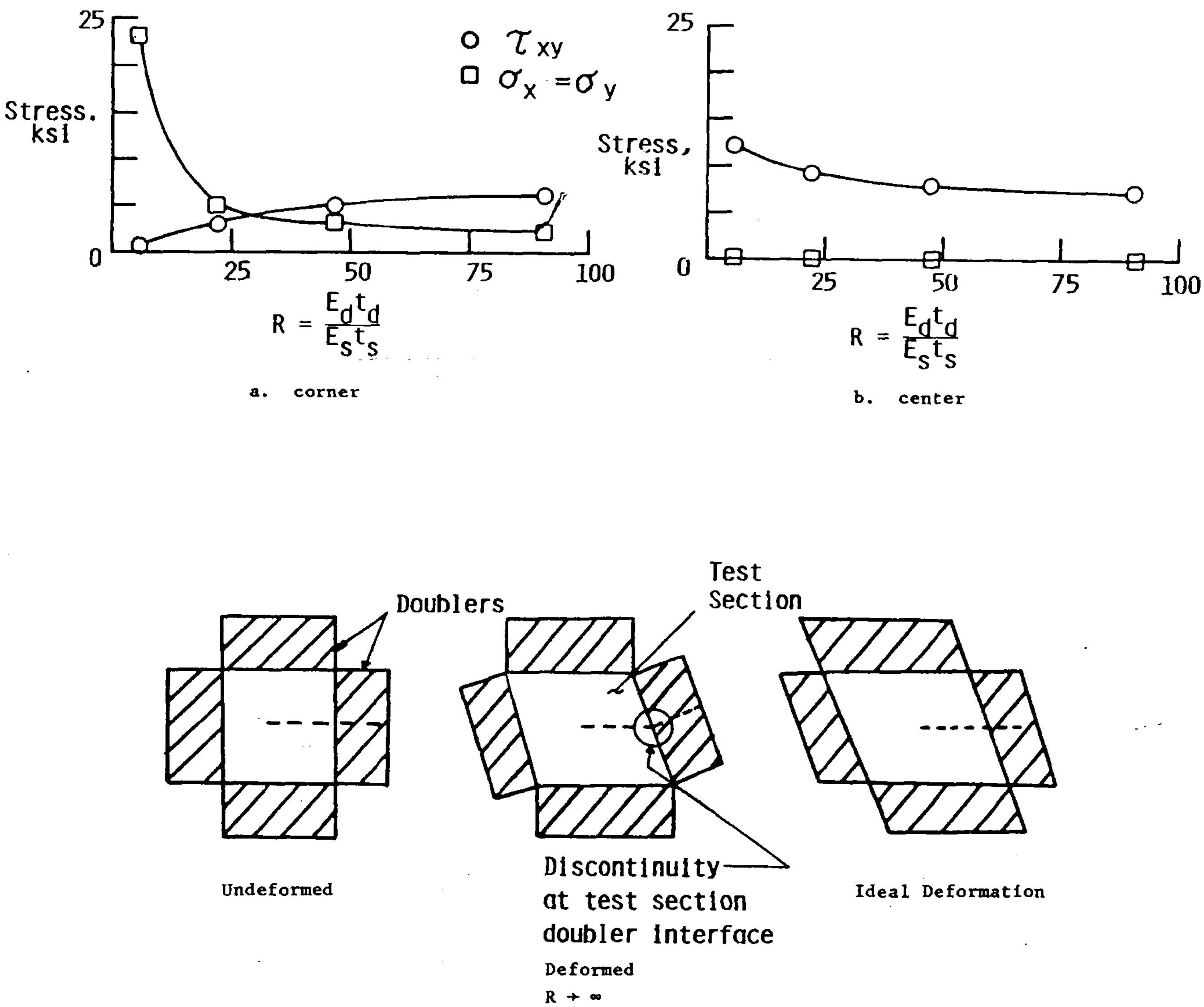


Figure 36. Variation of Stresses in the Test Section as a Function of Modulus-Thickness Ratio, R, and the Reason for this Variation [53], Reprinted with Permission of AIAA

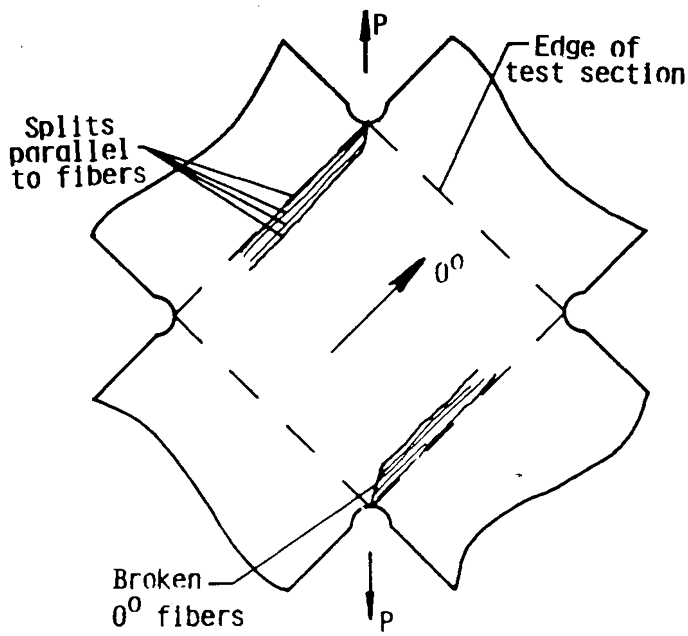


Figure 37. Damage in a $[0/45/90/-45]_{2s}$ Graphite/Epoxy Shear Specimen [53], Reprinted with Permission of AIAA

3.9.4 Other Considerations and Modifications

When sandwich specimen is not used, care must be taken to avoid buckling. Several attempts have been made to improve this test method as discussed earlier but without success. The fixtures required are too complicated and it does not appear worthwhile to attempt any additional effort for this purpose.

3.10 CROSS BEAM AND CRUCIFORM SPECIMEN

3.10.1 Description of the Test Methods

The cross beam specimen (Figure 38) is prepared by bonding composite laminates ($(0/90)_{ns}$ and $(\pm 45)_{ns}$ layups have been tested) to a honeycomb core [54]. A biaxial loading device is required to apply equal and opposite loads on the two cross arms. The face sheets in the test section is subjected to tensile and compressive stresses in two perpendicular

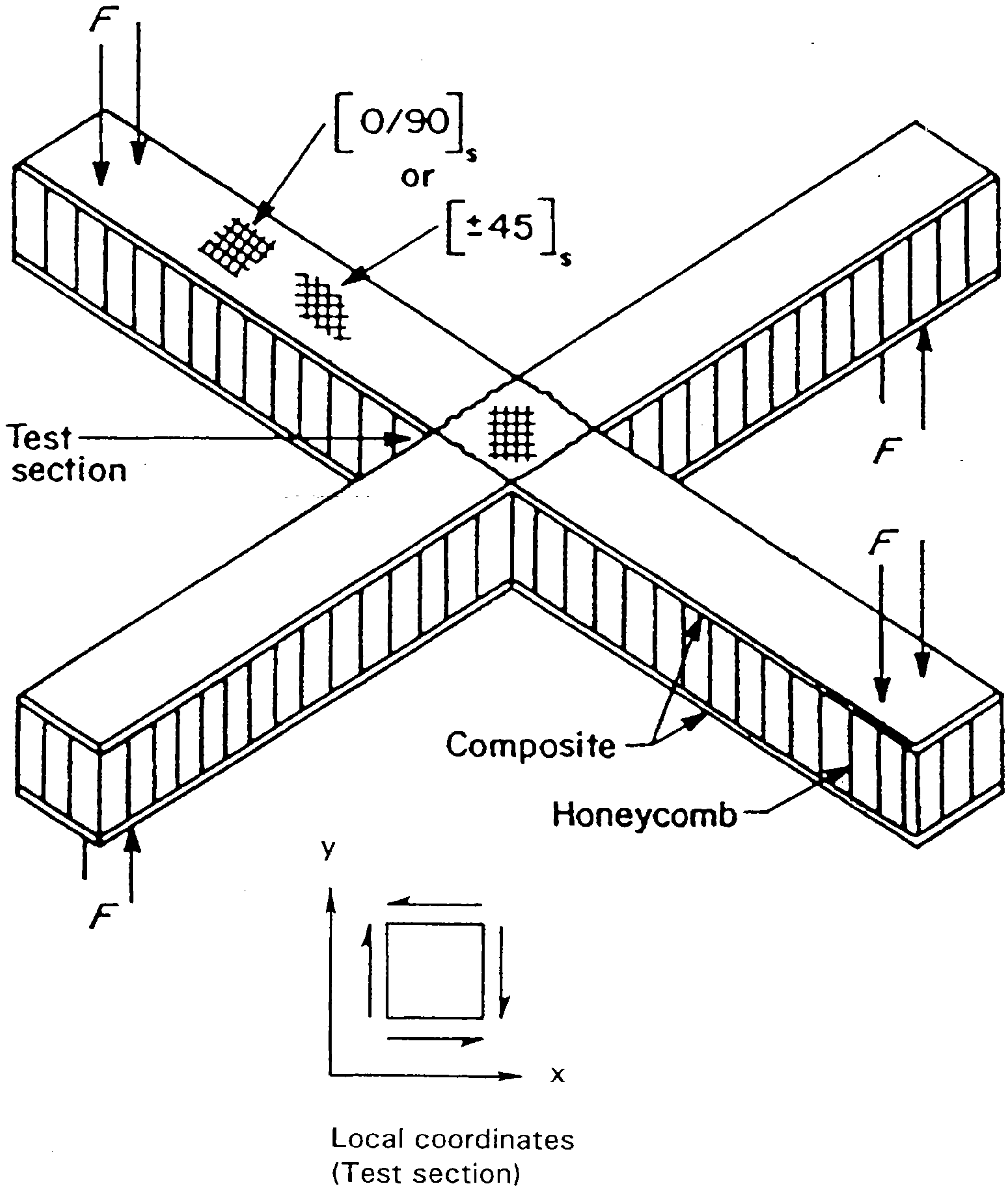


Figure 38. The Crossbeam Specimen [54], Reprinted from [46] by Permission of the Publishers Butterworth Heinemann Ltd. ©

directions (longitudinal axes of the two beam arms) and a state of shear stress is created at 45° to these directions (Figure 38). Thus, testing a (0/90) layup yields the shear response of a (±45) laminate whereas shear stress strain response of a cross ply layup is obtained from (±45) laminate face sheets. Some investigators [17, 55] have reported that reasonable data can be obtained, which are comparable to those from other methods.

To simplify specimen preparation procedures, testing of a cruciform laminate (in the same shape as the facesheets in the cross beam), which does not require bonding to honeycomb core, has also been attempted [56]. Tensile and compressive loads are applied to the two arms of the specimen by means of a stiff four bar linkage system similar to that used in loading the picture frame shear specimen discussed in the previous section.

3.10.2 Stress States and Failure Modes

Some finite element studies have been performed to analyze the stress distributions in the face sheets of the cross beam [27, 54] and the cruciform [56] specimens. The results for the cross beam with due consideration of the flexibility of the core and those for the cruciform are similar. Stress contours for a $(\pm 45)_{ns}$ cruciform specimen [56] are shown in Figures 39-41. The results for a quarter of the specimen are given normalized with the applied tensile and compressive stress, which is equal to the shear stress in the ideal case. It may be seen that the shear stress may be considered to be uniform over a small area in the center but it is different from unity. For $(0/90)_{ns}$ laminate, it is usually close to unity [27, 56]. However, for both types of laminates the stress state is far from ideal and there are problems in the (reentrant) corners. Normal stresses and their gradients are high [54], demonstrating the fact that there is some form of stress infinity at the corners and failures will initiate near the corners.

Failure mechanisms in cross beam specimens are not discussed much in the literature. Failure of cruciform specimens may occur because of instability, unless appropriate thickness is used or tabs are employed away from central test section [56]. However, back-to-back rosettes appear needed to check for bending or buckling possibilities. When buckling and bending effects are absent, failures initiate near the corners. Narrow strips of delaminations below the outer plies have been found to extend diagonally from corner to corner across the test section [56]. Use of rounded corners (0.3" radius) has been found to yield better stress

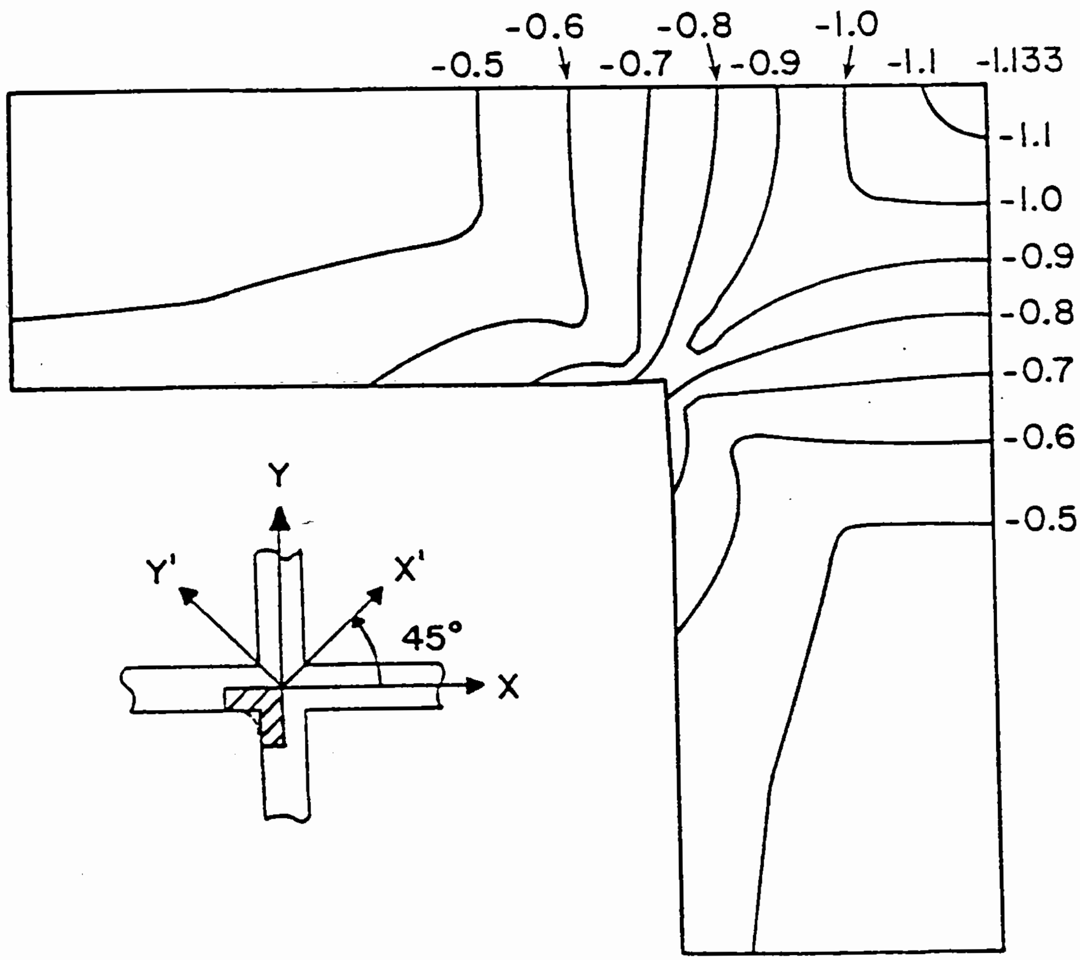


Figure 39. Normalized $\tau_{x'y'}$ Contours for a $[\pm 45]_s$ Cruciform Specimen with Sharp Corners [56], Reprinted with Permission

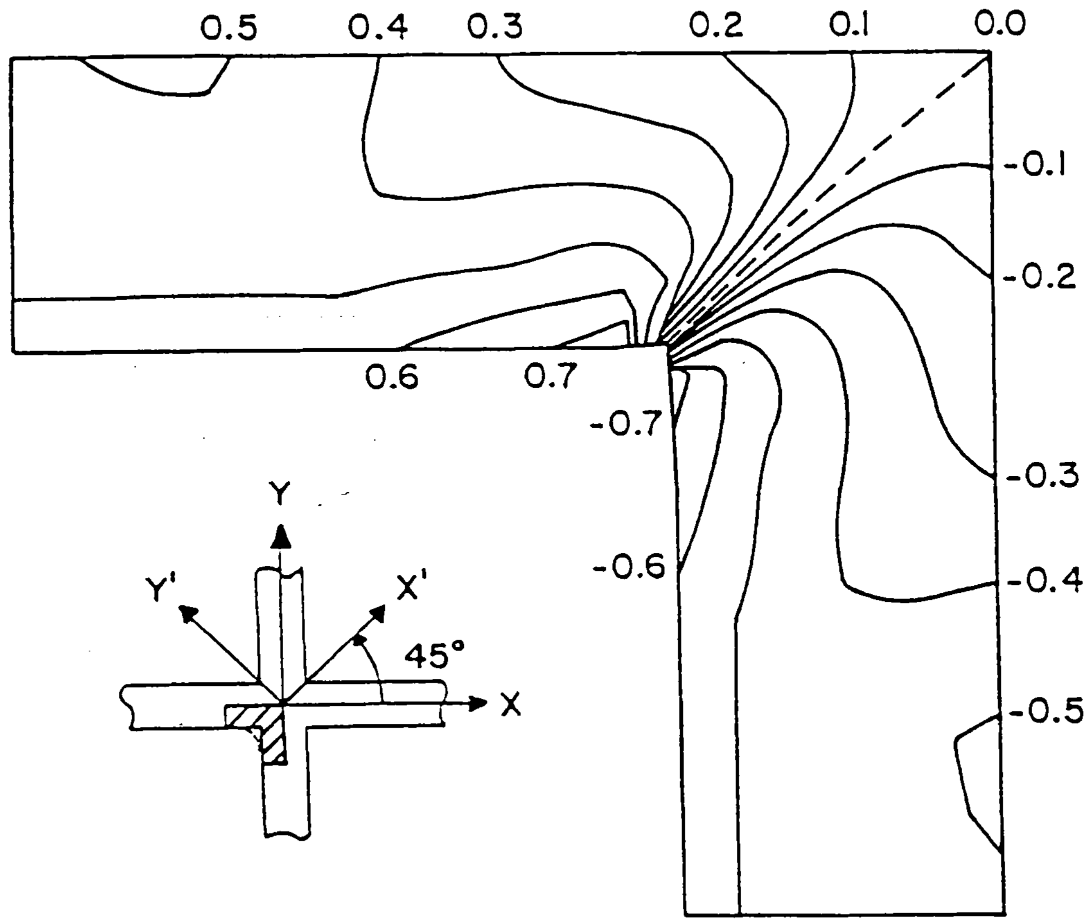


Figure 40. Normalized $\sigma_{x'}$ Contours for a $[\pm 45]_s$ Cruciform Specimen with Sharp Corners [56], Reprinted with Permission

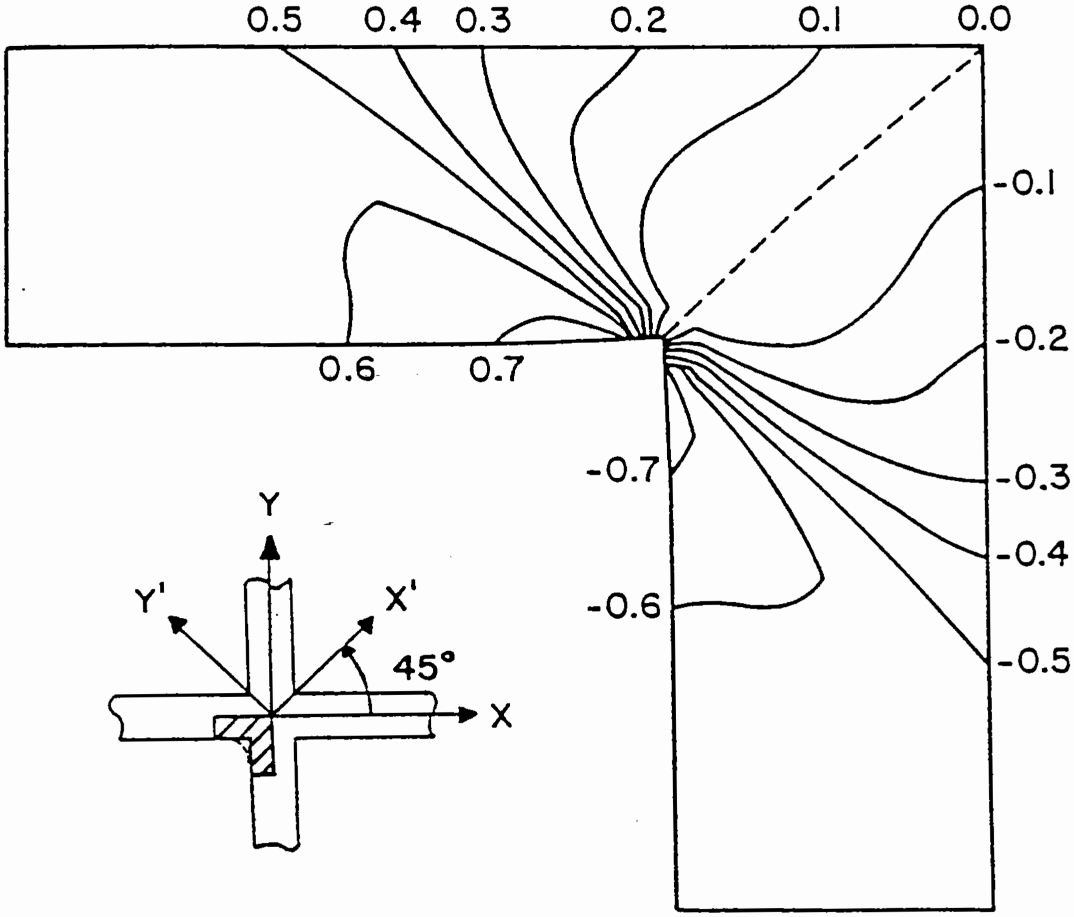


Figure 41. Normalized $\sigma_{y'}$ Contours for a $[\pm 45]_s$ Cruciform Specimen with Sharp Corners [56], Reprinted with Permission

distribution, but similar failure mechanisms. However, a band of delaminations initiate at the points where the rounding curves touch the edges of the specimen and extend inward. Stress-strain responses are slightly stiffer, and strengths and ultimate strains are higher when the corners are rounded [56]. The results from a small number of specimens are found to be comparable to those from other tests as reported in the literature. However, no conclusion can be reached at this point regarding consistency of test data from various sources. More test data are needed before this test can be considered acceptable.

Load introduction in the cross beam sandwich does not appear to be a problem. Effects of pin loading on the cruciform have been studied [56] and it has been found that a distance of 2" (twice the width of the arms) from the test section end to the pins is required. Aluminum tabs are bonded to the specimen arms at the pinholes to prevent failures at these locations. Use of proper adhesive may be needed for hot/wet testing, but no such testing is reported in literature.

3.10.3 Data Reduction

Shear stain is computed from three-element strain rosette data. A correction factor for shear stress (about 1.1) is required for ($\pm$45) specimens. Otherwise there is no complication in data reduction.

3.10.4 Other Considerations and Modifications

Specimen alignment errors may cause serious problems (bending) in $(0/90)_{ns}$ cruciform specimens. Fiber misalignment may cause some errors in all tests, but the effects have not been quantified. Use of rounded corners is needed to obtain better stress distribution as discussed earlier. Cruciform specimens with slits parallel to the arms produce more uniform stress distribution in the test section, but stresses near the slits are high [56] and early failure is expected in such specimens.

Considerable effort is needed in the preparation of the cross beam specimen. Preparation of the cruciform is also complicated. Special loading fixtures and devices are required for testing both types of specimens.

3.11 SLOTTED OR NOTCHED SHEAR

3.11.1 Description of the Test Method

Because of their simplicity, slotted shear specimens are often used to determine the shear strength, and various forms have been suggested (Figure 42 [57-59]). This is a simple tension test on a specimen containing two surface cuts or a more complicated arrangement of notches as shown in the figure, so that one or more shear paths are available. The shear strength is computed as the maximum load divided by the area of the path (or paths). Measurement of shear strain (and hence the modulus) cannot be performed. Use of the notched shear geometry is more common in interlaminar testing. An ASTM Standard (D3846-79 [60]) for plastics exists, in which compression load is applied. Lateral supports are required in compression testing. For tension loading, the situation is similar to shear testing of adhesives (ASTM D3165-73).

3.11.2 Stress States and Failure Modes

The stress state in the specimen is highly complex. Some finite element studies have been conducted [27, 58], which show high stress concentration at the rounded notch tips. Axial, stresses are extremely high. Transverse and shear stresses are also high. The stress distributions in a 0° specimen are shown in Figure 43. In this configuration, the spacing between the notches is 0.6 times the depth of the specimen and therefore, the nominal (average) shear stress = 1.67 $\bar{\sigma}$, $\bar{\sigma}$ being the applied tensile stresses. In the 0° specimen the shear stress is 0.6$\bar{\sigma}$ over a large portion of the shear path. Shear stresses near the notch tips are therefore high. A stress concentration factor of 1.57 is reported in [58] at the notch tip. A thin region of almost uniform shear stress ($\approx 0.6\bar{\sigma}$) exists in the center of the test area, indicating that a measure of the shear strength can possibly be obtained. However, the test can only be used for obtaining estimates or for comparison (quality control, etc.) purposes. The stress states in other lay-ups like 90° or ±45° are much more disturbed [27].

Failure modes in these specimens may be either due to shear along the shear path [58, 61] or by tensile (or compressive) failure along one of the notches [58] depending on reinforce-

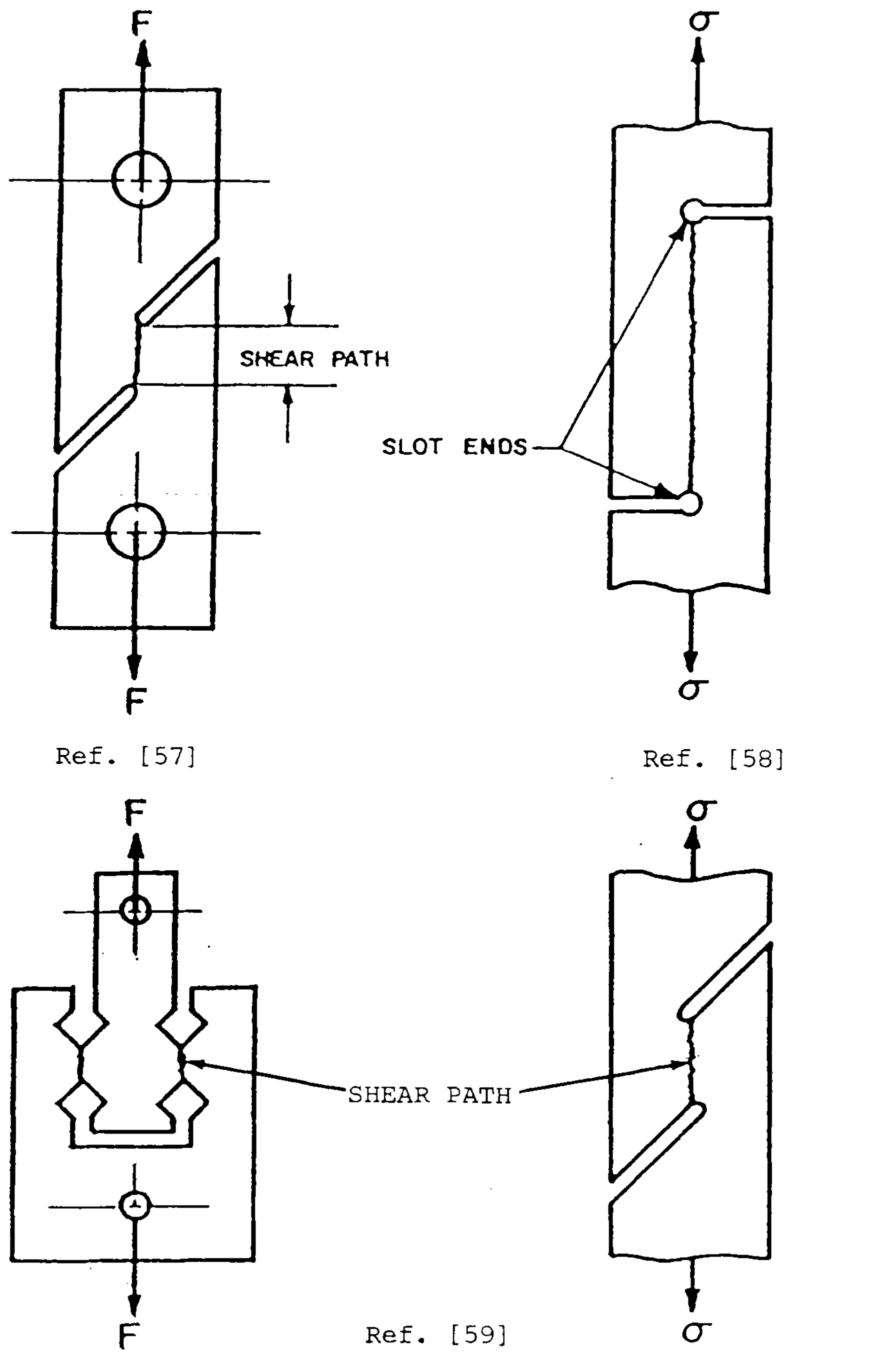


Figure 42. Slotted Shear Specimens [27], Reprinted with Permission

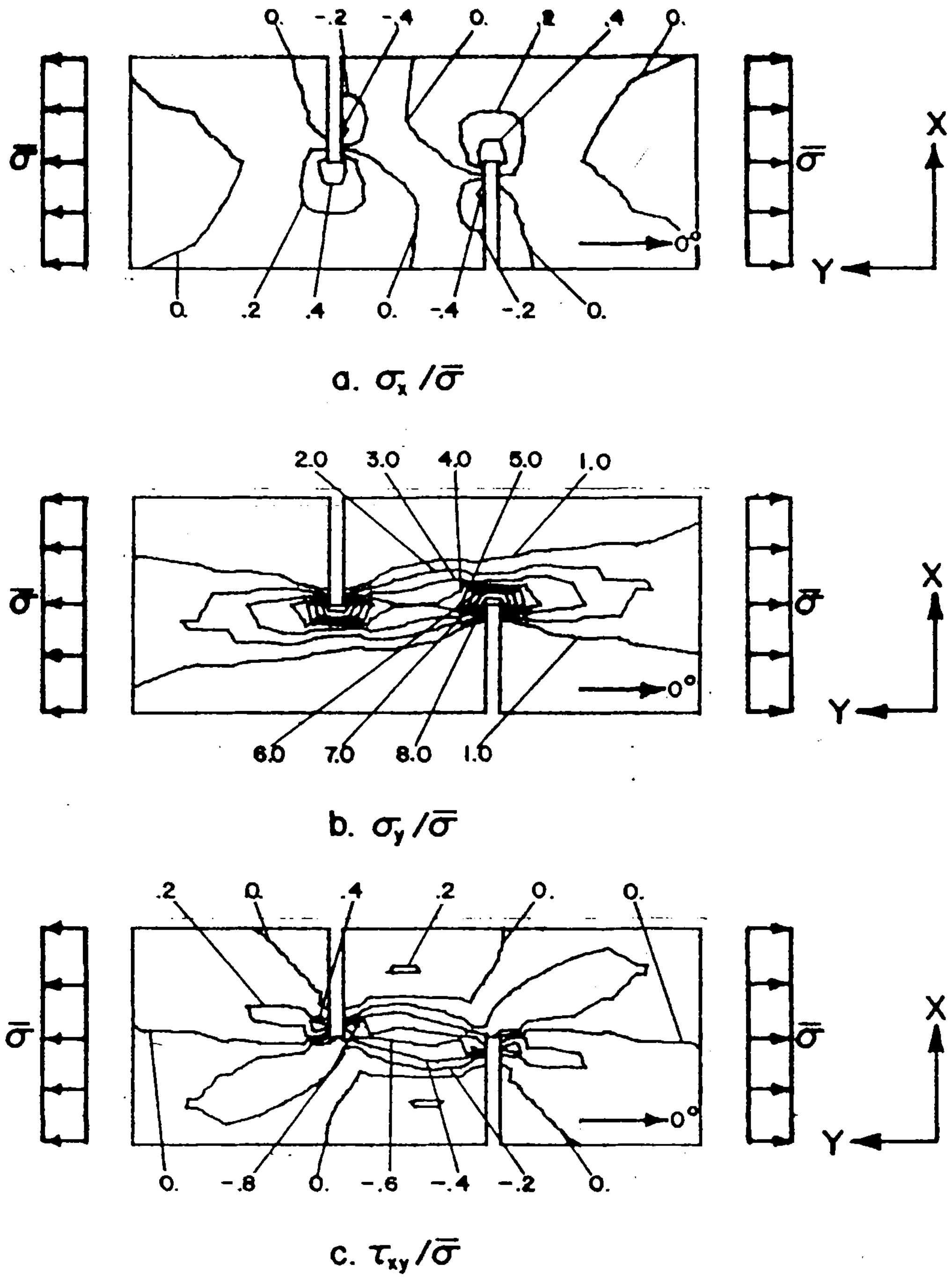


Figure 43. Normalized Stress Contours for [0] Slotted Shear Specimens, Spacing Between Notches = 0.6 x Depth of Specimen [27], Reprinted with Permission

ment types. In continuous fiber systems with no fibers crossing the shear path (0° material or interlaminar tests with other lay-ups with comparatively high axial strength) shear failure is expected. However, bending and peeling as well as tearing of the fibers are also noticed [9]. No data are available regarding consistency of results from different sources. However, data obtained are not very reliable [9]. Hot wet testing does not pose a problem.

3.11.3 Data Reduction

Only strength is measured and the nominal value is computed based on the area of the shear path. A better approach based on a shear lag type analysis and the assumption that the material is elastic/perfectly-brittle (failing in shear) is suggested in [61]. In this procedure test data are generated for various values of ℓ (the length of the shear path) and a curve-fitting procedure is employed to determine the strength, i.e. the maximum shear stress at the notch tip. However, it is quite likely that there are many other factors such as (i) damage induced by axial and transverse stresses and (ii) constrained damage growth or inelastic shear response, which possibly influence the results. A simple modification of the procedure given in [61], by assuming that the shear response is of elastic/perfectly-plastic type may possibly be attempted to improve the data reduction procedure.

3.11.4 Other Considerations and Modifications

For interlaminar tests thickness (depth) of the specimen is very small and it is often difficult to cut notches of required (half of the specimen) depth. A slight undercut gives higher strength where as overcuts reduce the strength. Bending and peeling are often observed in overcut specimens [9].

3.12 SHORT BEAM SHEAR

3.12.1 General Description of the Test Method

A three-point loaded beam is often used for determining interlaminar shear strength. An ASTM Standard (D2344-84 [62]) suggests that the span-to-depth ratio be equal to 5 for common unidirectional or cloth reinforced composites. Recommended width is of the order of the depth. 0.25" diameter loading cylinders (or noses) and 0.125" diameter support cylinders are often employed. Sufficient overhang length, of the order of the depth, is required. The fixture (Figure 44) allows for span and cylinder adjustments. Each of the two halves of the beam is subjected to a constant shear force. However, a bending moment also exists which is maximum at the point of application of the central load.

The bending moment as well as the pressure under the loading nose at the center can be reduced (for the same shear force) by using a four-point loaded beam [63]. A fixture for this system which allows adjustments in upper and lower spans is shown in Figure 45. However, test data [63, 64] do not indicate any marked improvement in shear strength by using the four-point loaded beam.

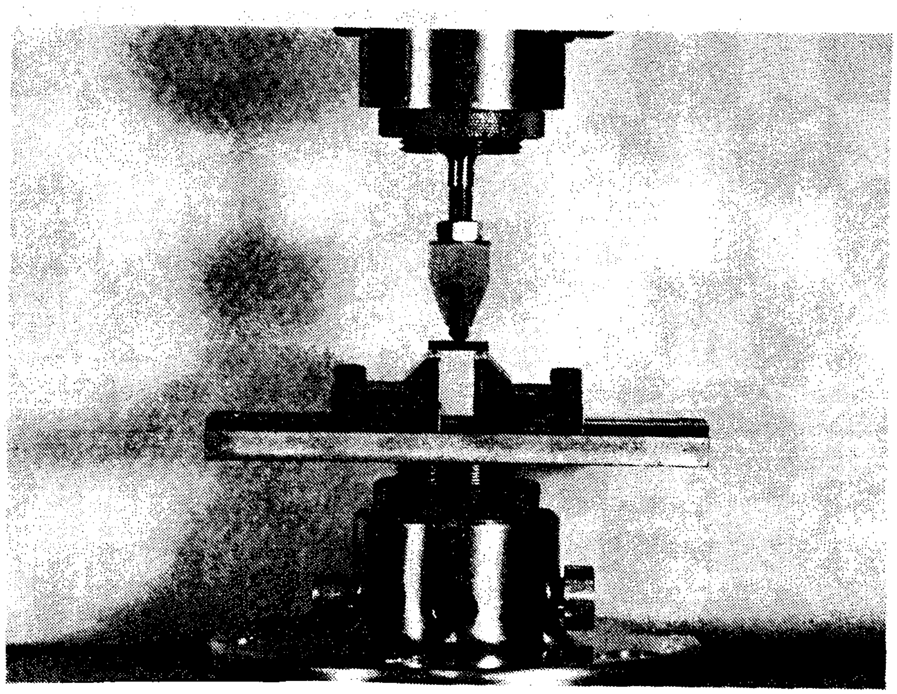


Figure 44. Three-Point Shear Fixture, Courtesy: D.F. Adams, University of Wyoming

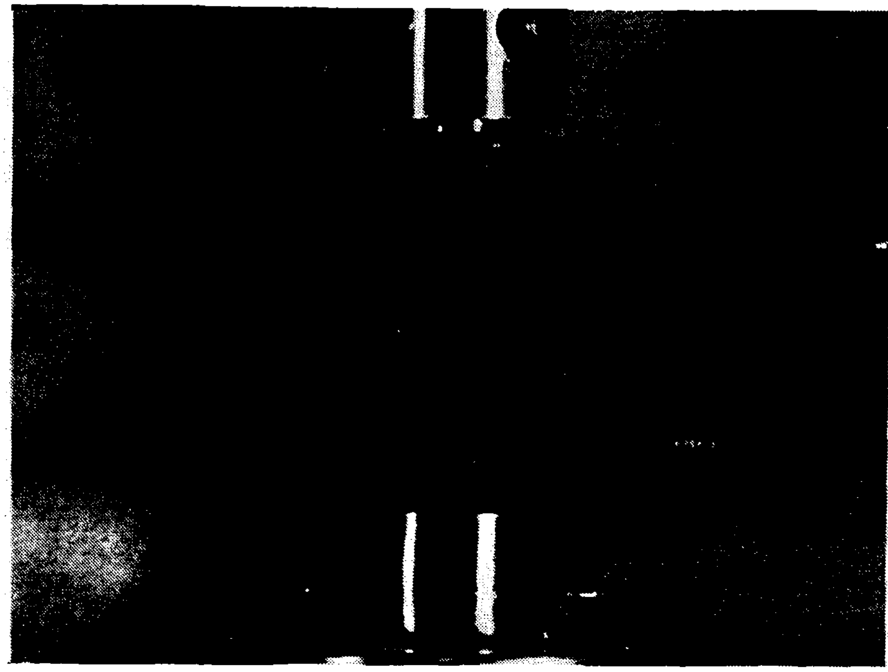


Figure 45. Four-Point Shear Fixture, Courtesy: D.F. Adams, University of Wyoming

3.12.2 Stress States and Failure Modes

The stress states in the specimens are highly complex. The shear stress variations for some geometries of the three-point loaded beam [65] are plotted in Figures 46 and 47. The results show that the wellknown parabolic variation of shear stress based on beam theory holds away from the loading points only when the span-to-depth ratio (ℓ/h) is large. Near the loading points the shear stresses are maximum not at the midplane but at planes closer to the loading noses. Further, for short spans ($\ell/h \leq 4$) the shear stress on the midplane can be lower than the nominal shear stress $\tau_o = 3P/4bh$ even away from the loading points [Figure 47].

In addition to the differences in shear stresses, the stress state is far from ideal because of high flexural stresses and contact stresses under the loading noses [66]. For this reason, failure in such beams often occurs due to a combination of compression (flexural), crushing and shear stresses. Most of the time the failure originates near the central loading nose [66].

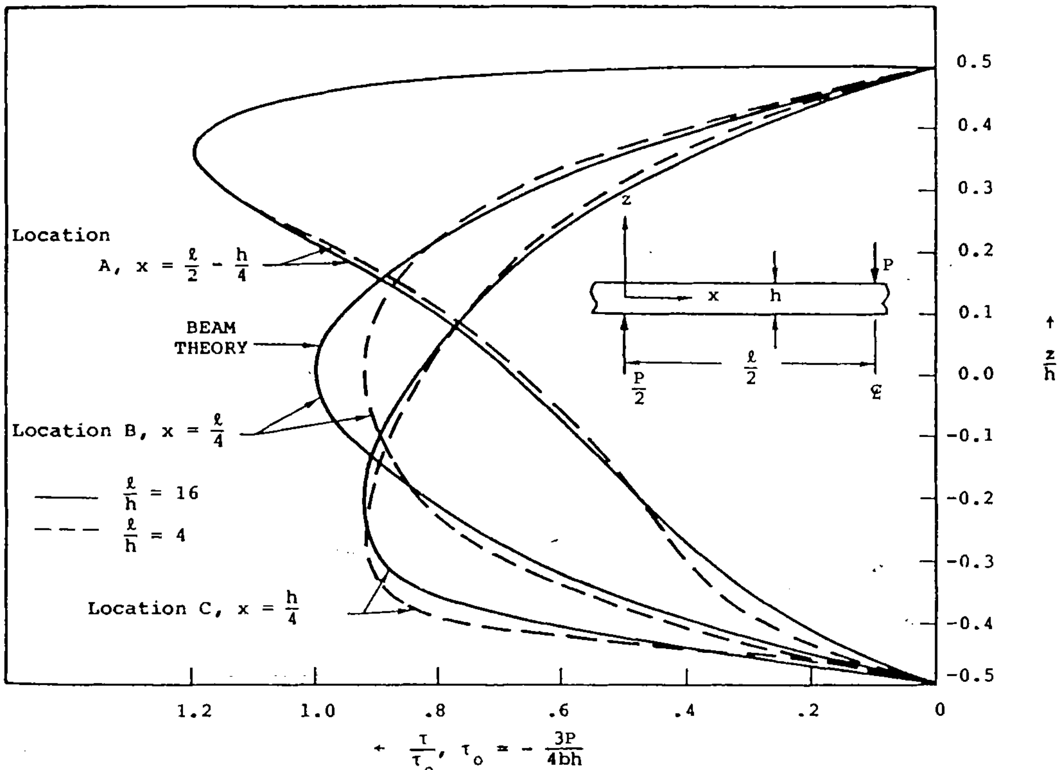


Figure 46. Shear Stress Distributions in Three-Point Loaded Beam [65]

Sometimes failure may occur only due to compression [67]. Damages may also occur above the reaction points [66]. Some guidelines for selecting a span-to-depth ratio to assure that failure will be due to shear are reported in [68], which is based on the assumption that failure will occur near the central loading point. However, these results are based on the beam theory solution, which is inaccurate near loading points. Therefore, it is a common practice to study the failure mode and examine the failure surface to make sure that failure has occurred due to shear for the chosen ℓ/h ratio.

In common glass/epoxy and graphite/epoxy composites, longitudinal cracks (one or more) are observed at or near the midplane for ℓ/h ratios varying from 3 to 7 [64]. Damage due to compressive flexural stress and crushing under the loading noses is found to be minimal. However, the apparent shear strength is found to increase monotonically as ℓ/h is decreased. No value of ℓ/h can be found below which the strength practically remains unchanged. Similar results are obtained from four-point loaded beams. It appears that unless ℓ/h is too high, shear failure will occur, and possible shear cracking under the loads is suppressed

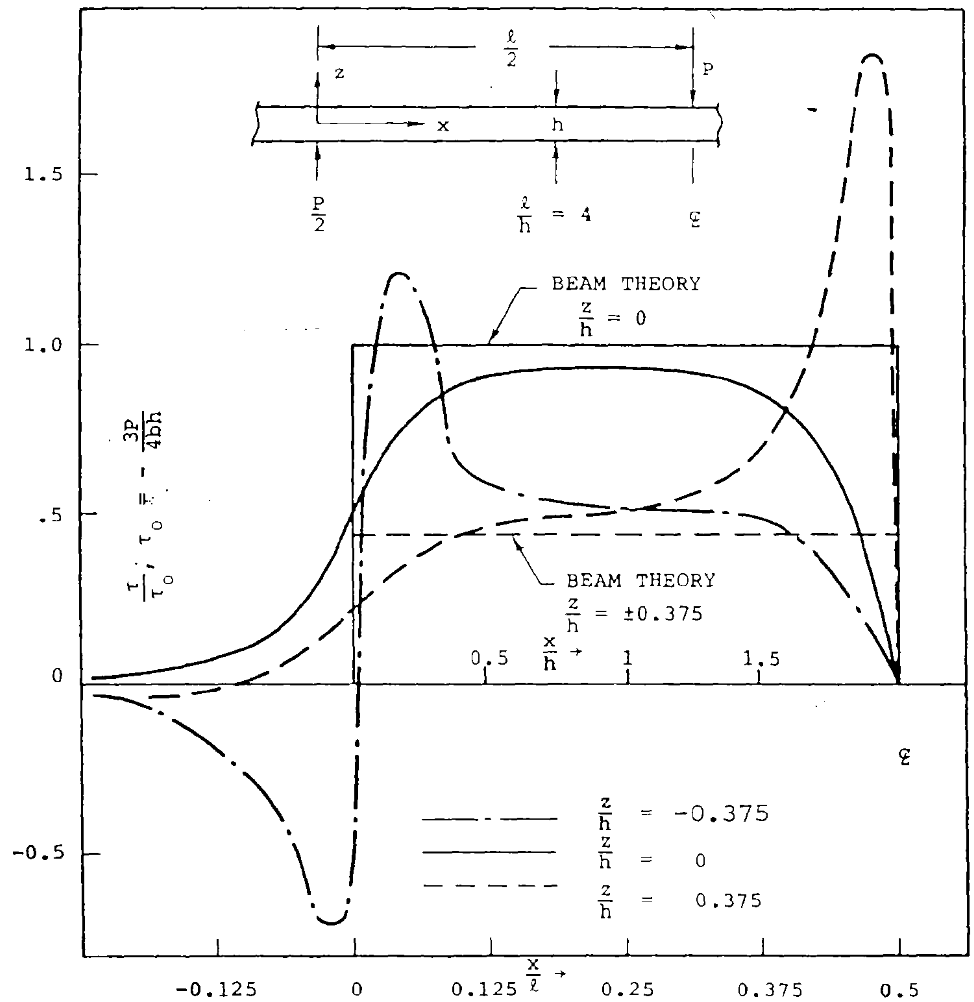


Figure 47. Shear Stress Variation Along Beam Axis in a Short Beam
ℓ/h = 4 [65]

because of high compressive stresses. Further, as stress analyses [Figure 47] suggest, the shear stress away from the loads becomes lower than the nominal value when the beam becomes shorter and therefore, the strength increases. Therefore, very short lengths are also not desirable in order to obtain the shear strength. Also, testing of very short beams should be avoided since only a very small volume of material will be subjected to the desired stress state.

Tests have also been conducted to determine the effects of the loading noses as well as width-to-depth ratio [64]. It has been observed that for common unidirectional materials width-to-depth ratio up to 6 may be employed even though analyses [68] suggest that W/h should be less than 3 to insure that shear stresses are not far off from beam theory solutions. However, the ratio should be of the order of unity when testing angle ply ($\pm\theta$) laminates. Variations in the diameters of the loading noses are not found to have much influence on the apparent shear strength unless they are too small [64].

It has been suggested [63] that, for the same ratios of the geometric dimensions, testing a thicker specimen is desirable to reduce the contact stresses under loading noses. However, test data indicate an increase in specimen thickness lowers the apparent shear strength [64], possibly due to the likelihood of having more critical flaws in a larger volume of material.

In general, the results are found to be consistent even from different sources provided the geometry of the specimen is the same. For reasons discussed earlier (and based on test data reported in literature) ℓ/h ratio should not be too high or too low. Values of the order of 5 to 6 for 0° graphite/epoxy and 3 to 4 for 0° glass/epoxy may be adequate. Stress analyses are needed to determine the ℓ/h ratio so that the nominal shear stress is recovered (away from the loads) for a given lay-up. Confirmation of shear failure from examination of failure surfaces is essential.

Hot wet testing does not pose a problem. However, in materials such as thermoplastics (and in some thermosets), large deformations may occur before failure, and in such cases definition of strength becomes a problem, since stress-strain response is usually not measurable. Measurement of load versus deformation data and a method to back out the shear response from deflection due to shear may be a way out of this problem, but accurate deflection measurement appears difficult.

3.12.3 Data Reduction

Data reduction based on nominal shear stress calculated from beam theory is simple. However, as discussed earlier, this approach gives only a measure of the strength since the stress state is highly complex.

3.12.4 Other Considerations and Modification

The four-point beam test discussed earlier has been studied as a possible modification. Test data reported in literature, however, do not show that this modification yields more reliable data. With proper geometric dimensions, the test is adequate for quality control purposes.

3.13 OTHER TESTS

3.13.1 General Description of the Test Methods

Various other tests have been proposed for measurement of shear modulus or strength. Some of them are discussed next. However, none of these tests has gained acceptance in the composites community.

Plate Twist - Square flat plates (Figure 48) are used to determine the shear modulus. Two upward forces are applied at the ends of a diagonal whereas two downward forces are applied at the other two corners. Deflection measurements are used to compute the modulus. Extreme care is needed in preparation of the sample and in load-deflection measurements. ASTM D3044-76 for plywood provides the details of the test. It has been used to determine the shear modulus of unidirectional materials [22]. There are, however, problems, since large deformations have significant influence on the response and the corners are susceptible to damage. In addition, warpage during curing can influence the deflection [69].

Four-Point Ring Twist - A four-point loaded circular beam of constant cross section undergoes a significant amount of deflection due to torsion (Figure 49 [70]). Measurement

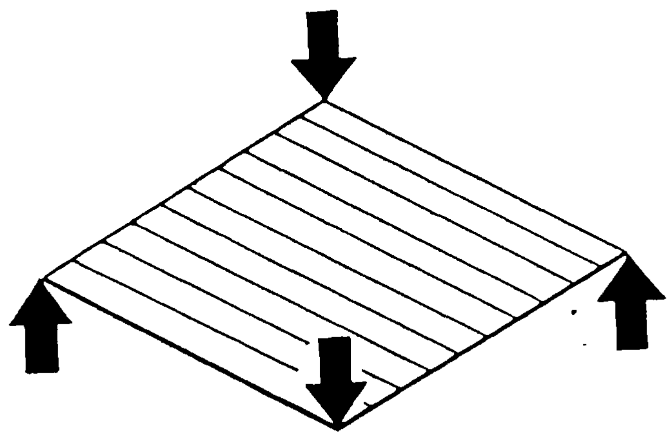


Figure 48. Plate Twist Test [69], Copyright ASTM, Reprinted with Permission.

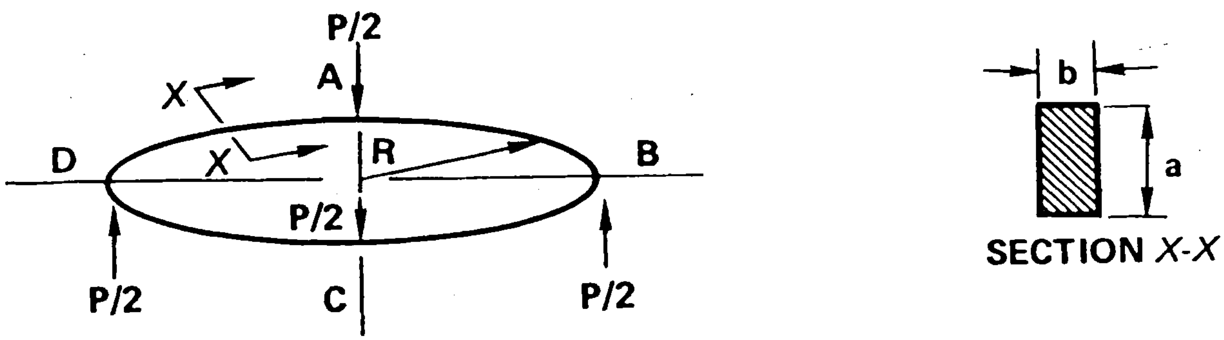


Figure 49. Four-Point Ring Twist Test [70], Copyright ASTM, Reprinted with Permission.

of total deflection and subtraction of bending deflecting yields a measure of the shear modulus of the unidirectional beam material. The test is suitable if the material is available in tube or ring form [70].

Split Ring Shear - A split ring (Figure 50) is subjected to equal and opposite forces at the split. Computed bending deflection is subtracted and the result is used to compute the shear modulus [69]. The test is useful for materials available in tube or ring form.

Biaxial Loading (Tension-Compression) of a Slotted Coupon - A tensile coupon containing slots (along the center line) parallel to loading direction is simultaneously subjected to compression on its edges (Figure 51 [54, 71]). This causes equal tensile and compressive stresses over a large portion of the coupon [54, 71] and a state of pure shear at 45°. The axially oriented slots insure that the compressive load is transferred through the central test section. Without slots the load will diffuse and distribute in an unknown manner. Although the test should be able to yield the complete stress strain response, only modulus and strength values are reported [71]. 0°, (0/90), (±45), (0/±45) and (0/±45/90) layups have been tested. Finite element calculations [71] show that shear stresses at the center are within 2% of nominal value, but there is some stress concentration (10%) at the slot end. The process of biaxial loading is, however, complicated, since the tensile specimen has to be installed in a pin guided transverse compression fixture [71]. For this reason this test has not been used by any other investigator.

Block Shear - Single as well as double block shear tests (Figure 52) have been employed by some investigators [72, 73]. The stress state, however, is complex. It can possibly yield qualitative data.

Lap Shear - A measure of strength may be obtained [74, 75], but the stress state is complex and failure is caused by combined action of peel and shear stresses (Figure 53).

Button Torsion - A specimen in the form of a button is bonded to fixtures and a torsional moment is applied. A possible loading arrangement [74] is shown in Figure 54. Stress state is complex and singularities exist at the bond zone boundary.

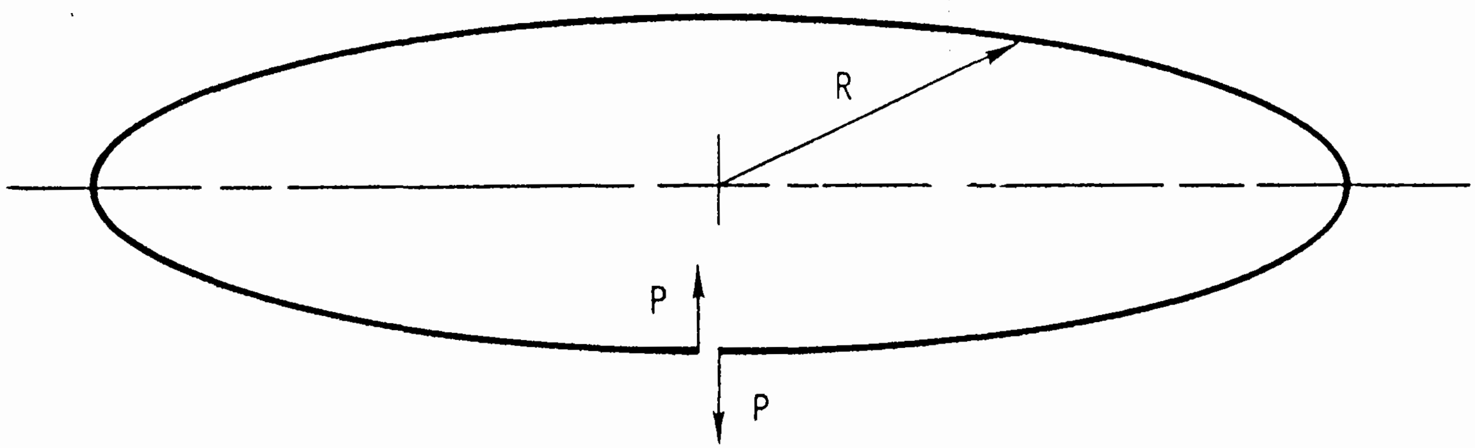


Figure 50. Split Ring Shear Test [69], Copyright ASTM. Reprinted with Permission.

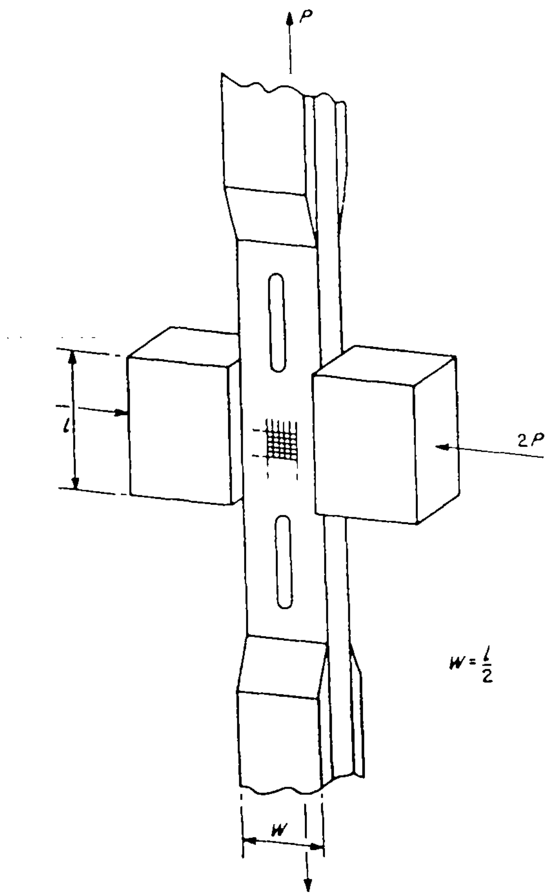


Figure 51. Slotted Biaxial Specimen [54, 71], Reprinted from [46] by Permission of the Publishers Butterworth Heinemann Ltd. ©

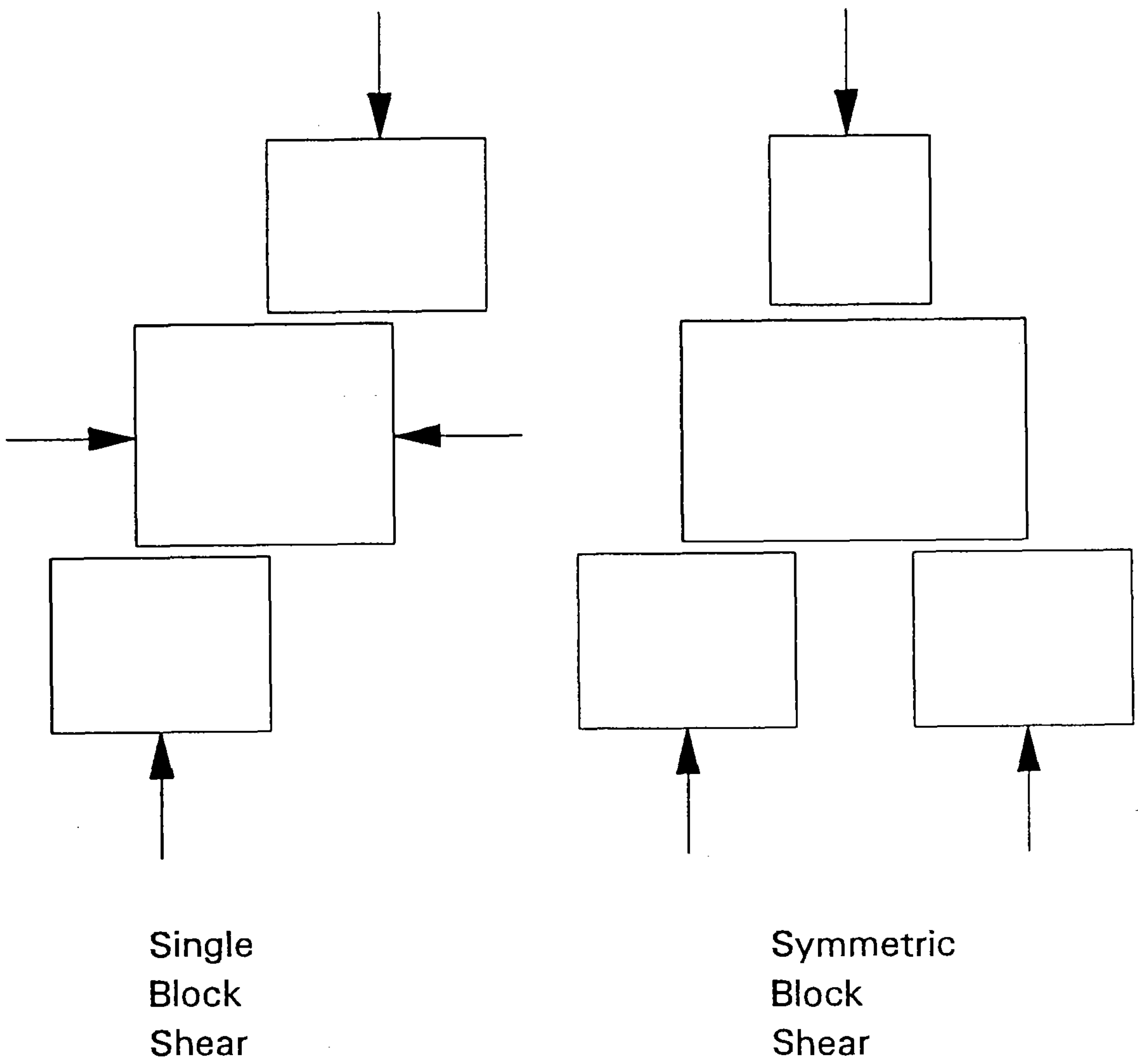
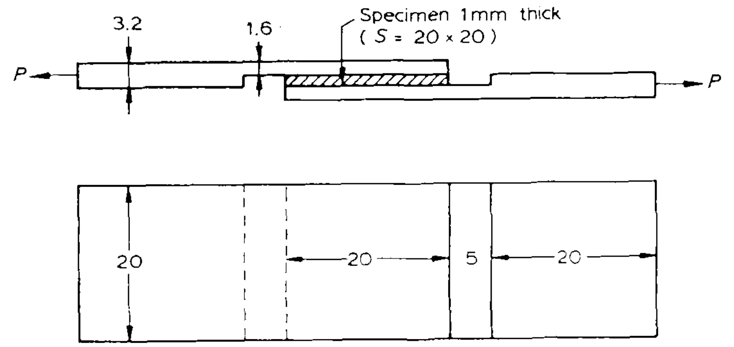
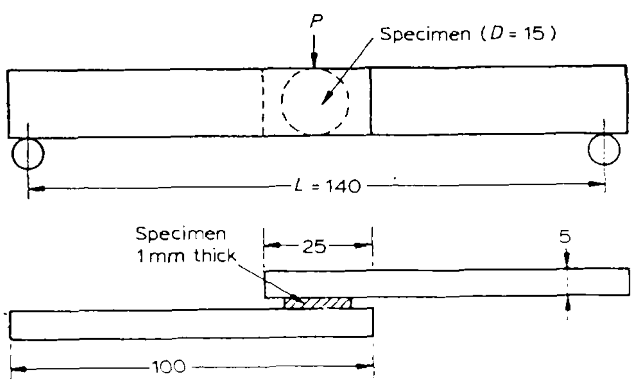


Figure 52. Block Shear Tests [72]



$$\tau_m = \frac{P_m}{S} \quad (kg/mm^2)$$

Figure 53. Lap Shear Test Reprinted from [74] by Permission of the Publishers Butterworth Heinemann Ltd ©



$$\tau_m = \frac{2P_m L/2}{\pi (D/2)^3} \quad (kg/mm^2)$$

Figure 54. Button Torsion, Reprinted from [74] by Permission of the Publishers Butterworth Heinemann Ltd. ©

Slant Shear - In a modified version of the lap shear test, a compressive load is applied thus avoiding the peel stress problem (Figure 55). Shear strength is found to depend on the compressive stress on the failure plane and, hence, it really yields the strength under such combined stresses [75].

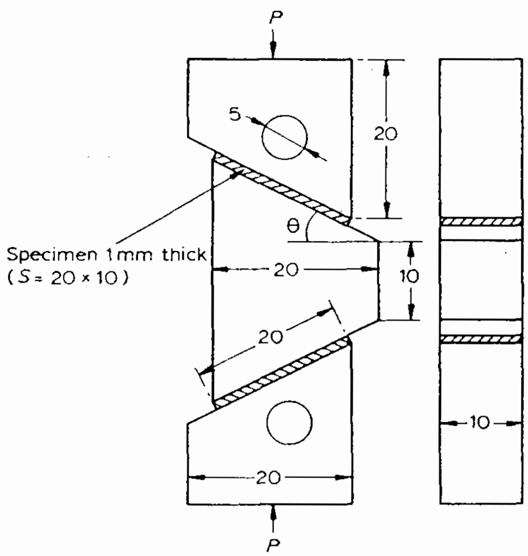


Figure 55. Slant Shear Test, Reprinted from [74] by Permission of the Publishers Butterworth Heinemann Ltd. ©

REFERENCES

(References marked with an * are also summarized in the Bibliography)

* 1. Bucinell, R., "Interim JANNAF Test Method for In-Plane Shear Properties of Unidirectional Fiber/Resin Composite Cylinders", Interim Report for MIL-HDBK-17, AMTL Contract DAAL04-89-C-0023, 1991.

* 2. Marloft, R.H., "Finite Element Analysis of Bi-Axial Stress Test Specimen for Graphite/Epoxy and Glass Fabric/Epoxy Composites", ASTM STP 787, pp. 34-49, 1982.

* 3. Whitney, J.M. and Halpin, J.C., "Analysis of Laminated Anisotropic Tubes under Combined Loading", Journal of Composite Materials, Vol. 2, pp. 360-367, 1968.

* 4. Pagano, N.J. and Whitney, J.M., "Geometric Design of Composite Cylindrical Characterization Specimens", Journal of Composite Materials, Vol. 4, pp. 360-378, 1970.

* 5. Rizzo, R.R. and Vicario, A.A., "A Finite Element Analysis for Stress Distribution in Gripped Tabular Specimens", ASTM STP 497, pp. 68-88, 1972.

* 6. Foley, G.A., Roylance, M.E., and Houghton, W.W., "Use of Torsion Tubes to Measure In-Plane Shear Properties of Filament Wound Composites", ASTM STP 1003, pp. 208-223, 1989.

* 7. Swanson, S.R., Toombes, G.R., and Beckwith, S.W., "In-Plane Shear Properties of Composites Using Torsion Tests of Thin Walled Tubes", Proc. 29th SAMPE Symposium, pp. 567-577, 1984.

* 8. Swanson, S.R., Messick, M., and Toombes, C.R., "Comparison of Torsion Tube and Iosipescu In-Plane Shear Test Results for a Carbon Fiber Reinforced Epoxy Composite", Composites, Vol. 16, pp. 220-224, 1985.

* 9. Chiao, C.C., Moore, R.L., and Chiao, T.T., "Measurements of Shear Properties of Fiber Composites, Part 1. Evaluation of Test Methods", Composites, Vol. 8, pp. 161-169, 1977.

* 10. Phillips, D.C and Scott, J.M., "The Shear Fatigue of Unidirectional Composites", Composites, Vol. 8, pp. 233-236, 1977.

* 11. Chatterjee, S.N., Wung, E.C.J., Yen, C.F., Ramnath, V., Kessler, J.A., and Adams, D.F., "Composite Specimen Design Analysis, Vol. I: Analytical Studies, Vol. II: Experimental Effort", MTL TR 91-5, 1991.

* 12. Lenoe, E.M., Knight, M., and Schoene, C., "Preliminary Evaluation of Test Standards for Boron Epoxy Laminates", ASTM STP 460, pp. 122-139, 1969.

* 13. Sumsion, H.T. and Rajapakse, Y.D.S., "Simple Torsion Test for Determining the Shear Moduli of Orthotropic Composites", Composite Technology Review, Vol. 1, p. 8, 1979.

* 14. Ramnath, V. and Chatterjee, S.N., "Composite Specimen Design Analysis", MSC TFR 1701/1703, AMTL Contract DAAG46-85-C-0058, 1986.

15. Chatterjee, S.N. and Buesking, K.W., "Elasto-Plastic Torsion - A Variational Formulation and Incremental Solution", in <u>Advances in Aerospace Structures and Materials</u>, Proc. ASME Winter Annual Meeting, AD-01, ASME, New York, pp. 231-237, 1981.

16. "Standard Practice for In-Plane Shear Stress-Strain Response of Unidirectional Polymer Matrix Composites", ASTM Standard D3518-91, American Society for Testing of Materials, Philadelphia, PA, 1991.

* 17. Petit, P.H., "A Simplified Method of Determining the In-Plane Shear Stress-Strain Response of Unidirectional Composites", ASTM STP 460, pp. 83-93, 1969.

* 18. Rosen, B.W., "A Simple Procedure for Experimental Determination of the Longitudinal Shear Modulus of Unidirectional Composites", Journal of Composite Materials, Vol. 6, pp. 552-554, 1972.

* 19. Hahn, H.T., "A Note on the Determination of the Shear Stress Strain Response of Unidirectional Composites", Journal of Composite Materials, Vol. 7, pp. 383-386, 1973.

20. Kellas, S. and Morton, J., "Scaling Effects in Angle-Ply Laminates", NASA Contractor Report 4423, February, 1992.

* 21. Kellas, S., Morton, J., and Jackson, K.E., "An Evaluation of the ± 45 Tensile Test for the Determination of the In-Plane Shear Strength of Composite Materials", Proc. ICCM VIII, 1991.

* 22. Terry, G., "A Comparative Investigation of Some Methods of Unidirectional, In-Plane Characterization of Composite Materials", Composites, Vol. 10, pp. 233-237, 1979.

* 23. Sim, D.F., "In-Plane Shear Stress Strain Response of Unidirectional Composite Materials", Journal of Composite Materials, Vol. 7, pp. 124-128, 1973.

24. Iosipescu, N., "New Accurate Procedure for Single Shear Testing of Metals", Journal of Materials, Vol. 2, pp. 537-566, 1967.

* 25. Walrath, D.E. and Adams, D.F., "Verification and Application of the Iosipescu Shear Test Method", University of Wyoming Report UWMB-DR-401-103-1, 1984.

* 26. Sleepetz, J.M., Zageski, T.F., and Novello, R.F., "In-Plane Shear Test for Composite Materials", AMMRC TE 78-30, 1978.

* 27. Bergner, H.W., Jr., Davis, J.G., Jr., and Herakovich, C.T., "Analysis of Shear Test Method for Composite Laminates", Department of Engineering Science and Mechanics, VPI&SU, Report VPI-E-77-14, 1977.

* 28. Ho, H., Tsai, M.Y., Morton, J., and Farley, G.L., "An Evaluation of the Iosipescu Specimen for Composite Materials Shear Property Measurement", Center for Composite Materials and Structures, VPI&SU, Report CCMS-91-18, August 1991.

* 29. Abdallah, M.G. and Gascoigne, H.E., "The Influence of Test Fixture Design on the Iosipescu Shear Test for Fiber Composite Materials", ASTM STP 1003, pp. 231-260, 1989.

* 30. Lee, S. and Munroe, M., "Evaluation of Testing Techniques for the Iosipescu Shear Test for Advanced Composite Materials", Journal of Composite Materials, Vol. 24, pp. 419-440, 1990.

* 31. Ifju, P. and Post, D., "A Compact Double-Notched Specimen for In-Plane Shear Testing", Proc. SEM Conference, Cambridge, MA, 1989.

* 32. Arcan, M., Hashin, Z., and Voloshin, A., "A Method to Produce Uniform Plane-Stress States with Applications to Fiber-Reinforced Materials", Experimental Mechanics, Vol. 18, pp. 141-146, 1978.

33. Voloshin, A. and Arcan, L., "Failure of Glass-Epoxy Lamina-Fractrographic Study", Journal of Composite Materials, Vol. 13, pp. 240-246, 1979.

34. "Standard Guide for Testing In-Plane Shear Properties of Composite Laminates", ASTM Standard D4255-83, American Society for Testing of Materials, Philadelphia, PA, 1983.

* 35. Garcia, R., Weisshar, T.A., and McWhitney, R.R., "An Experimental and Analytical Investigation of the Rail Shear Test Method as Applied to Composite Materials", Experimental Mechanics, Vol. 20, pp. 273-279, 1980.

* 36. Black, J.B. and Hart-Smith, L.J., "The Douglas Bonded Tapered Rail-Shear Test Specimen for Fibrous Composite Laminates", Proc. 32nd National SAMPE Symposium, pp. 360-371, 1987.

* 37. Butler, R.J., Barnard, P.M., and Curtis, P.T., "The Development of a Satisfactory, Simple, Shear Fatigue Test for Unidirectional E-Glass/Epoxy", ASTM STP 972, pp. 227-240, 1988.

38. Kar, R.J., "Composite Failure Analysis Handbook, Vol. I - Program Overview", WL-TR-91-4032, DOT/FAA/CT-91/23, February, 1992.

* 39. Lockwood, P.A., "Results of ASTM Round Robin on the Rail Shear Test for Composites", Composite Technology Review, Vol. 3, pp. 83-86, Summer 1981.

* 40. Chamis, C.C. and Sinclair, J.H., "10° Off-Axis Test for Intralaminar Shear Characterization of Fiber Composites", NASA TN D-8215, 1976.

* 41. Nemoth, M.P., Herakovich, C.T., and Post, D., "On the Off-Axis Test for Unidirectional Composites", Composite Technology Review, Vol. 5, pp. 61-68, 1983.

* 42. Sandhu, R.S. and Sendeckyj, G.P., "On Design of Off-Axis Specimens", AFWAL-TR-84-3098, 1985.

* 43. Pindera, M.J. and Herakovich, C.T., "Shear Characterization of Unidirectional Composites with Off-Axis Tension Test", Experimental Mechanics, Vol. 26, pp. 103-112, 1986.

* 44. Sun, C.T. and Berreth, S.P., "A New End Tab Design for Off-Axis Tension Test for Composite Materials", Purdue University, HTMIAC Report 5, 1987.

* 45. Cron, S.M., Palazotto, A.N., and Sandhu, R.S., "The Improvement of End Boundary Conditions for Off-Axis Tension Specimen", Experimental Mechanics, Vol. 28, pp. 14-19, 1988.

* 46. Lee, S. and Munroe, M., "Evaluation of In-Plane Shear Test Methods for Advanced Composites by Decision Analysis Technique", Composites, Vol. 17, pp. 13-20, 1986.

* 47. Farley, G.L. and Baker, D.J., "In-Plane Shear Test of Thin Panels", Experimental Mechanics, Vol. 23, pp. 81-88, 1983.

* 48. Bush, H.G. and Weller, T., "A Bi-Axial Method for In-Plane Shear Testinn", NASA TM 74070, 1978.

* 49. Bryan, E.L., "Photoelastic Investigation of the Panel Shear Test for Plywood", ASTM STP 289, pp. 90-94, 1961.

* 50. Dastin, S, Lubin, G., Munyak, J., and Slobodzinski, A., "Mechanical Properties and Test Techniques for Reinforced Plastic Laminates", ASTM STP 460, pp. 13-26, 1969.

* 51. Hadcock, R.N. and Whiteside, J.B., "Special Problems Associated with Boron Epoxy Mechanical Test Specimens", ASTM STP 460, pp. 27-36, 1969.

* 52. Douglas, D.O., Holzmacher, D.Z., Lane, Z.C., and Thornton, E.A., "Studies in Finite Element Analysis of Composite Material Structures", Old Dominion University Report 75-M3, 1975.

* 53. Kennedy, J.M., Barnett, T., and Farley, G.L., "Analysis of the Picture Frame In-Plane Shear Test for Composite Materials", Proc. AIAA/ASME/ASCA/AHS 28th SDM Conference, pp. 402-407, 1987.

* 54. Duggan, M.F., McGrath, J.T., and Murphy, M.A., "Shear Testing of Composite Materials by a Combined Loading Technique, Proc. AIAA/ASME SDM Conference, pp. 311-319, 1978.

* 55. Waddoups, M.E., "Characterization and Design of Composite Materials", in <u>Composite Materials Workshop</u>, Tsai, S.W., Halpin, J.C., and Pageno, N.J., Editors, Technomic, pp. 254-308, 1968.

* 56. Barnett, T.R., "An Experimental and Analytical Evaluation of a Bi-Axial Test for Determining Shear Properties of Composite Materials", M.S. Thesis, Clemson University, April 1988.

57. Breindel, W.W., Seale, C.L., and Carlson, R.L., "Evaluation of a Single Shear Specimen for Sheet Material", Proc. ASTM, Vol. 56, p. 862, 1958.

* 58. Elkin, R.A., Fust, G., and Hanley, D.P., "Characterization of Graphite Fiber/Resin Matrix Composites", ASTM STP 460, pp. 321-335, 1969.

59. Bert, C.W., "Experimental Characterization of Composites", in <u>Composite Materials</u>, Broutman, L.J. and Krock, R.H., Editors, Vol. 8, p. 95, 1974.

60. "Standard Test Method for In-Plane Shear Strength of Reinforced Plastics", ASTM Standard D3846-79, American Society for Testing of Materials, Philadelphia, PA 1979.

* 61. Markham, M.F. and Dawson, D., "Interlaminar Shear Strength of Fiber Reinforced Composites", Composites, Vol. 6, pp. 173-176, 1975.

62. "Standard Test Method for Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short Beam Method", ASTM Standard D2344-84, American Society for Testing of Materials, Philadelphia, PA, 1989.

* 63. Browning, C.L., Abrams, F.L., and Whitney, J.M., "A Four Point Shear Test for Graphite Epoxy Composites", ASTM STP 797, pp. 54-74, 1983.

* 64. Lewis, E.Q. and Adams, D.F., "An Evaluation of Composite Material Shear Test Methods", University of Wyoming Report UW-CMRG-R-91-103, May 1991.

65. Fiber Composite Analysis and Design, Volume II, Structures, B. Walter Rosen, Editor, DOT/FAA/CT-88/18, FAA Technical Center, Atlantic City, NJ, 1988.

* 66. Berg, C.A., Tirosh, J., and Israeli, M., "Analysis of Short Beam Bending of Fiber Reinforced Composites", ASTM STP 497, pp. 205-218, 1971.

* 67. Stinchcomb, W.W., Henneke, E.G., and Price, H.L., "Use of the Short Beam Shear Test for Quality Control of Graphite Polyamide Laminates", ASTM STP 626, p. 96, 1977.

* 68. Sattar, S.A. and Kellogg, D.H., "The Effect of Geometry on the Mode of Failure of Composites in the Short Beam Shear Test", ASTM STP 460, pp. 62-71, 1969.

* 69. Greszczuk, L.B., "Shear Modulus Determination of Isotropic and Composite Materials", ASTM STP 460, pp. 140-149, 1969.

* 70. Greszczuk, L.B., "Applications of Four Point Ring-Twist Test for Determination of Filamentary Composites", ASTM STP 734, pp. 21-33, 1981.

* 71. Duggan, M.F., "An Experimental Evaluation of the Slotted-Tension Shear Test for Composite Materials", Experimental Mechanics, Vol. 20, pp. 233-239, 1980.

* 72. Peters, P.W.M., "The Interlaminar Shear Strength of Unidirectional Boron Aluminum Composites", Journal of Composite Materials, Vol. 12, pp. 53-62, 1978.

* 73. Zabora, R.F. and Bell, J.E., "A Test Technique to Study Interlaminar Shear Phenomenon of Laminated Fiber Composites", AFFDL-TR-71-67, 1971.

* 74. Kadotani, K. and Aki, F., "Analysis of the Interlaminar Shear Strength of Mica/Epoxy Insulations", Composites, Vol. 15, pp. 57-60, 1984.

* 75. Adsit, N.R., McCutchen, H., and Forest, J.D., "Shear Testing of Advanced Composites", Proc. 6th Symposium Composite Materials in Engineering Design, p. 448, 1972.

APPENDIX

ANNOTATED BIBLIOGRAPHY

IN PLANE AND INTERLAMINAR SHEAR TESTS

(Items marked with * are also refernced in body of the report.)

*** ITEM NO. 1**

AUTHORS: Abdallah, M.G. and Gascoigne, H.E.

TITLE: The Influence of Test Fixture Design on the Iosipescu Shear Test for Fiber Composite Materials

SOURCE: ASTM STP 1003

pp: 231-260

DATE: 1989

TEST SPECIMENS: Iosipescu and Asymmetric four point bend

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Results of analytical studies as well as tests and photoelastic investigations are reported. Effects of tabs, 90° notch angle and rounded notch tips are considered. Good correlation is observed between finite element and photoelasticity results.

Alignment of specimens within the fixture is difficult and may cause out of plane moment (twisting) of the specimen. APFB fixture produce more symmetric shear stress distribution than Iosipescu fixtures and it also gives less problems in alignment. Friction may cause larger scatter in data.

Area of constant shear strain is small (.06 inch in width). Tabbing may not affect stress distribution but improves strength and suppresses crushing.

Failure in 90° specimen may occur away from the notch because of twisting effects. First cracks in 0° and 90° specimens may occur due to combined action of shear and normal stresses.

ITEM NO. 2

AUTHORS: Adams, D.F.

TITLE: Mechanical Testing of Composite Materials for Quality Control

SOURCE: 3rd International Congress on Composites, Weisbaden, Germany
pp:

DATE: October, 1991

TEST SPECIMENS: Various

CONTENTS:

Experimental Results? [Y/N] - N   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Reviews various test methods - tensile, compressive, inplane and interlaminar shear as well as flexure and their applications for quality control. Lack of standardization is discussed.

*** ITEM NO. 3**

AUTHORS: Adsit, N.R., McCutchen, H., and Forest, J.D.

TITLE: Shear Testing of Advanced Composites

SOURCE: Proc. 6th Symposium, Composite Materials in Engineering Design
pp: 448-

DATE: 1972

TEST SPECIMENS: Double lap shear

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Reports that combined stresses exist at critical points. Failure may be due to tensile as well as shear stresses and the mode is ambiguous.

*** ITEM NO. 4**

AUTHORS: Arcan, M., Hashin, Z., and Voloshin, A.

TITLE: A Method to Produce Uniform Plane-Stress States with Applications to Fiber-Reinforced Materials

SOURCE: Exp.Mech., 18

pp: 141-146

DATE: 1978

TEST SPECIMENS: Arcan

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Concepts for the Arcan test specimen are discussed and results are presented. A butterfly shaped composite specimen (similar to Iosipescu test sections) bonded to an aluminum disk with tabs was suggested later. Supplementary experiments reported elsewhere (Voloshin, A and Arcan, M., Fiber Sci. & Technology, 13, 1980, p. 125) indicate that results are not affected by slight variation of shear stress through the test section.

*** ITEM NO. 5**

AUTHORS: Barnett, T.R.

TITLE: An Experimental and Analytical Evaluation of a Biaxial Test for Determining Shear Properties of Composite Materials

SOURCE: M.S. Thesis, Clemson University

pp:

DATE: August, 1988

TEST SPECIMENS: Cruciform specimen

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Advantages and disadvantages of cross beam sandwich, slotted tensile and cruciform specimens under biaxial loading are reviewed. Cruciform specimens with and without slots and rounded corners are analyzed in detail for (0/90) and (±45) layups. Test data are found to be in good agreement with analytical results when rounded corners are used. It appears that such a geometry is acceptable when buckling or bending problems are avoided with proper specimens and tabs as well as alignment. However, the fixture needs tight tolerances and is massive.

*** ITEM NO. 6**

AUTHORS: Berg, C.A., Tirosh, J., and Israeli, M.

TITLE: Analysis of Short Beam Bending of Fiber Reinforced Composites

SOURCE: ASTM STP 497

pp: 205-218

DATE: 1971

TEST SPECIMENS: Short beam shear

CONTENTS:

Experimental Results? [Y/N] - N   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Maximum shear stress may be underestimated, combined stress (incl. of bi-axial compression) under loading nose may initiate early fracture. Analysis includes elasto-plastic response.

*** ITEM NO. 7**

AUTHORS: Bergner, H.W., Jr., Davis, J.G., Jr., and Herakovich, C.T.

TITLE: Analysis of Shear Test Method for Composite Laminates

SOURCE: VPI-E-77-14

pp:

DATE: 1977

TEST SPECIMENS: Slotted shear, Cross beam shear, Iosipescu, Two rail shear

CONTENTS:

Experimental Results? [Y/N] - N Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Information applicable to unidirectional (or cross ply) specimens is listed below.

Slotted Shear

Analysis performed for ideal end conditions.

A narrow strip between the slots may be considered to have uniform shear stress. Its magnitude is much smaller than the average value (≈ load (slot spacing x thickness)). High axial and transverse stresses also exist in the region. Stresses are very high near the notches. The test may yield qualitative data but useless for quantitative measurement.

Data reduction process is not defined without detailed analysis of stress and strain and hence modulus cannot be measured.

Cross Beam Shear

Analyses reported for ±45 (for cross ply shear response) and 0/90 (for ±45 properties).

Significant extensional stress exist near the edges of the test section and at the corner, but they become small near the center.

The stress state is highly complex and nonuniform except for a small area at the center. Shear stress is higher than average value (1.13 to 1.2 times).

Iosipescu

Results reported for rigid and elastic fixtures which are different from the University of Wyoming type fixture now being used widely. The fixture studied here is complicated. Stress distributions differ somewhat from those discussed in other works (see item 23 for example), but they are qualitatively similar. It is, however, shown that thermal stresses due to temperature change are not of significance in this fixture.

Two Rail Shear

Rigid rails as well as elastic tapered rails are studied. Results are similar to those discussed in other works (see item 23, for example).

ITEM NO. 8

AUTHORS: Bert, C.W.

TITLE: Static Testing Techniques for Filament Wound Composite Materials

SOURCE: Composites, 5

pp: 20-26

DATE: 1974

TEST SPECIMENS: Various

CONTENTS:

Experimental Results? [Y/N] - N   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Review of various test methods. Discusses strong effect of inaccuracies in fiber direction on data from axial test and off-axis tests. Specimen length to width ratio for 3 or more is suggested for off-axis specimens. Also discusses various other shear specimens.

*** ITEM NO. 9**

AUTHORS: Black, J.B., and Hart Smith, L.J.

TITLE: The Douglas Bonded Tapered Rail-Shear Test Specimen for Fibrous Composite Laminates

SOURCE: 32nd Natl. SAMPE Symposium

pp: 360-371

DATE: 1987

TEST SPECIMENS: Two rail shear

CONTENTS:

Experimental Results? [Y/N] - N Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Bonded tapered rail shear test is analyzed. It is shown than that the severe stress singularities which occur at the loaded corners (at rail-free edge junction, as identified in the work of Ramnath and Chatterjee in item 23 which led them to suggest the use of a parallelogram shaped specimen) may be weakened by the presence of inelastic or soft adhesive layers. Only (±45) material is considered. It is also pointed out that use of this test yields very high strengths of (±45) materials as compared to other tests. Some limits on specimen thicknesses are also discussed.

ITEM NO. 10

AUTHORS: Broughton, W.R., Kumosa, M., and Hull, D.

TITLE: Analysis of the Iosipescu Shear Test as Applied to Unidirectional Carbon Fibre Reinforced Composites

SOURCE: Composite Sci. & Technology

pp: 299-326

DATE: 1990

TEST SPECIMENS: Iosipescu, Torsion tube

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Force-couple as well as displacement boundary conditions are considered in finite element analyses of 0° and 90° Iosipescu specimens with sharp 90° notches. First set of boundary conditions appear to be consistent with photoelastic results. Correction factors are suggested for determining the shear stress in the gage section. Moduli (with correction factors) for 0° and 90° specimens appear to be within 10% of torsion tube data. Catastrophic failure is observed in 90° Iosipescu specimens. Axial splitting and resulting longitudinal cracks in 0° specimens tend to promote more uniform shear stress distribution. After such splitting, the response becomes increasingly nonlinear and secondary failures under load occur a little later due to interply failure and/or crushing. The stress level at this point compares well with strength obtained in hoop wound torsion tubes for graphitic epoxy materials. Torsion tube data are, however, lower than the stress level for axial splitting in case of Gl/Polyester composites. Failure modes of brittle and ductile systems for 0° and 90° orientations are discussed.

*** ITEM NO. 11**

AUTHORS: Browning, C.E., Abrams, F.L. and Whitney, J.M.

TITLE: A Four Point Shear Test for Graphite Epoxy Composites

SOURCE: ASTM STP 797

pp: 54-74

DATE: 1983

TEST SPECIMENS: Short Beam Shear

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Reports analytical and experimental results for 3-point and 4-point loaded beams. Suggests the use of thick specimens or 4-point loaded specimen.

*** ITEM NO. 12**

AUTHORS: Bryan, E.L.

TITLE: Photoelastic Investigation of the Panel Shear Test for Plywood

SOURCE: ASTM STP 289

pp: 90-94

DATE: 1961

TEST SPECIMENS: Picture frame

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Photoelastic investigation showed the stress state to deviate from pure shear. However, in critical areas (on edge) pure shear exists and the test should yield a good measure of shear strength.

*** ITEM NO. 13**

AUTHORS: Bucinell, R.

TITLE: Interim JANNAF Test Method for In-Plane Shear Properties of Unidirectional Fiber/Resin Composite Cylinders

SOURCE: Interim Report for MIL-HDBK-17, AMTL Contract DAAL04-89-C-0023
pp:

DATE: 1991

TEST SPECIMENS: Torsion tube

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Reports from round robin. Results encouraging for proposed standard.

Length between grips/diameter $\approx$ 1.0, sufficient for avoiding end effects from internal and external gripping fixtures bonded to specimen with potting compound.

Thickness to diameter ratio $\approx$ .02 to yield nearly uniform stress in gage section.

Because of ($\pm 89.5°$) lay up (fibers at 0.5° from hoop direction) some constraints exist for cracks in hoop direction and failure strains are of the order of 4 to 4.5% which appear to yield data needed for practical application. Failure occurs away from grips.

Data reduction is simple even in nonlinear range and methods are described.

• ITEM NO. 14

AUTHORS: Bush, H.G. and Weller, T.

TITLE: A Bi-Axial Method for In-Plane Shear Testing

SOURCE: NASA TM 74070

pp:

DATE: 1978

TEST SPECIMENS: Picture frame

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: First significant developments of the method. Pinning of specimen to frames, cut out at corners, and use of doublers near the free edge are suggested to reduce high stresses near the corners. Use of sandwich with a honeycomb core is also suggested to avoid buckling problems. Biaxially loaded test frame subjects the specimen to a more or less uniform shear strain.

• ITEM NO. 15

AUTHORS: Butler, R.J., Barnard, P.M., and Curtis, P.T.

TITLE: The Development of a Satisfactory Simple, Shear Fatigue Test for Unidirectional E-Glass/Epoxy

SOURCE: ASTM STP 972

pp: 227-240

DATE: 1988

TEST SPECIMENS: Two rail shear

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] -

REMARKS: It is suggested that standard rail shear tests with fibers parallel to rails show large scatter in shear strength (or fatigue life) because of formation of stable or unstable cracks near the loaded ends or corners due to transverse tensile strain concentration (confirmed by finite element analyses). The scatter is shown to be reduced by the introduction of 1/2" long slots in the specimen at all the corners at the locations of the rail boundaries. These slots tend to stop unstable crack growth. The slotted specimen also has a higher load capability and larger stiffness based on reduced gage length due to slots. Finite element analyses with surface pressure (shear) loads on the specimen show shear strains in the center of the two specimens to be comparable for the same load. Results also compare well with test data for strains. The results indicate that appropriate correction factors are possibly required for determining shear stress in the gage section.

<u>* ITEM NO. 16</u>

AUTHORS: Chamis, C.C. and Sinclair, J.H.

TITLE: 10° Off-Axis Test For Intralaminar Shear Characterization of Fiber Composites

SOURCE: NASA TN D-8215

pp:

DATE: 1976

TEST SPECIMENS: 10° Off-axis

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: End effects are discussed and found to be of some importance (later studies show that corrections are needed to consider aspect ratio effect L/W). Edge effects present, although minimal, create generation of cracks near edges.

Stress state is more or less uniform but transverse stresses exist.

Failure is usually by crack propagation starting from an edge. Fracture strains of MOD-I/Ep are comparable to 90° torsion tube test (about 1%) and higher than ±45 test. S-glass/Ep and T300/Ep ultimate strains are high (≈ 3.5%). These results are not in agreement with other investigations which show much lower failure strains as compared to ±45 tests for Gr/Ep specimens.

*** ITEM NO. 17**

AUTHORS: Chatterjee, S.N., Wung, E.C.J., Yen, C.F., Ramnath, V., Kessler, J.A., and Adams, D.F.

TITLE: Composite Specimen Design Analysis - Vol. I: Analytical Studies, Vol. II: Experimental Effort

SOURCE: MTL TR 91-5

pp:

DATE: 1991

TEST SPECIMENS: ±45, Iosipescu, Two rail shear, Torsion of circular and rectangular bars, Off axis tension. Short beam shear and Iosipescu (for interlaminar shear)

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Reports results of analyses and tests for various laminate specimens. Following informations are important for unidirectional lay-ups.

General

Initial modulus can be determined from all tests if proper stress correction factors or data reduction schemes are employed.

Off-axis Test

Stress correction factor required, which depends on material, off-axis angle and length/width ratio to account for end effects. Use of special fixtures required to allow rotation at ends.

Transverse tension exists.

Specimens usually fail very early because of transverse tension and unconstrained growth of cracks.

($\pm$45) Tension

See previous item for discussion on edge effect, stress state.

Transverse cracks in outer and inner plies along with delaminations are the reasons for failure. Thick specimens $(\pm 45)_{4s}$ yield higher failure stresses and strains, but values are much lower than Iosipescu and Rail Shear Specimens. Strains at failure are slightly less than torsion test data.

Two Rail Shear

Analyses for tapered rails show reduction of stress at unloaded corner near free edge, but high stresses exist near the loaded corner. These stresses may be reduced somewhat by using a parallelogram shaped specimen. However, these high stresses may not cause early failure because of load redistribution.

Stress state is fairly uniform over a large area, but some transverse stress and high axial stress (which may not be critical if fibers are in this direction) exist. A correction factor (1.051 for Gr/Ep) is required for shear stress. Use of three-element rosettes is recommended.

Tests on specimens with fibers perpendicular to rails (90° orientation) show some transverse cracking possibly due to shear (this is expected). However, these cracks cannot propagate catastrophically and possibly for this reason parallelogram shaped specimens appear to yield a response comparable to that from Iosipescu specimens and much higher strains to failure ($\approx$ 6%) as compared to $\pm$45 and torsion tests. Rectangular shaped specimens fail at lower strains possibly because of high stresses at the corner.

Iosipescu

Larger specimens (3" x 0.75" as opposed to 2" x 0.5") with 22% notch depth on each side and 90° or 120° rounded notch provide good shear stress distribution (correction factor of 0.84 or 0.93, respectively are required). Because of larger size loads are removed further from gage section thus reducing the transverse compressive stress (90° notch yield higher transverse stress). Axial stresses are low, but three-element rosettes should still be utilized. Even with the larger specimen a very small area (about 0.3" x 0.3") is subjected to the desired stress state.

Load drops occur because of splitting parallel to fibers near the notches, but the splits remain constrained as they propagate towards load points. Shear failures (or cracks) are not noticeable between the notches; possibly because of compressive transverse stresses. It is not clear whether these constraints yield higher strains to failure ($\approx$5%) as compared to ($\pm$45) and torsion tests.

<u>Torsion Tests on Solid Bars</u>

End effects can be minimized by choosing length-to-diameter ratio for > 20 for circular bars and length-to-width ratio > 15 for rectangular bars. Specimens of rectangular cross-sections with a thickness of 24 to 48 plies and at least 0.5" wide are adequate.

Stress state is nonuniform in circular bars, but it does not appear to be a drawback. It is, however, complex in rectangular specimens.

Strengths are comparable to Iosipescu or rail shear tests, but ultimate strains are lower ($\approx$3.2%). Damage progression appears to be slower in the beginning but not much constrained (as compared to Iosipescu or Rail shear) in the later stages.

Data reduction in the nonlinear range is simple for circular bars but complicated (based on stress analysis for elastoplastic material response) for rectangular ones. The latter procedure needs improvement.

<u>Other Information</u>

Stress states are better in both Iosipescu and Rail shear specimens for crossply lay-ups. Constrained ply crack growth occurs in both specimens, strains to failure are high and stress-strain response is comparable to those from similar specimens with unidirectional materials.

Short beam shear and Iosipescu tests were conducted for interlaminar shear strengths. 0° short beam data yield slightly lower strengths when l/d =4 as compared to those for l/d = 3 possibly because of flexure effects. (0/90) short beam shear strengths are higher than those from Iosipescu specimens, which may be due to nonlinear shear response in short beam case and/or edge effects in Iosipescu test. They however compare well with 0° data (short beam shear and inplane shear).

*** ITEM NO. 18**

AUTHORS: Chiao, C.C., Moore, R.L., and Chiao, T.T.

TITLE: Measurement of Shear Properties of Fiber Composites Part 1. Evaluation of Test Methods

SOURCE: Composites, 8

pp: 161-169

DATE: 1977

TEST SPECIMENS: Torsion tube, ±45, Short beam shear, Torsion of solid rod, Slotted shear, Off-axis.

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Review various test methods. Reports that torsion tube, solid bar torsion and ±45 tension yield comparable data up to the point of failure of torsion tube. ±45 and solid bars in torsion do not fail even at 2% strain level (for Kevlar 49/Ep). Response of solid bar from angle of twist appears to be less stiff (possibly because of the presence of adhesive bonding of end fixtures) than that from strain gage data. Torsion tube appears to yield the lowest modulus. 10° off axis test yields lower strength and ultimate strain even with coated edges.

±45 test without tabs is recommended because of its reproducibility and other advantages. However, mixed mode effects are present in this test.

For slotted shear of laminates (interlaminar properties) it is difficult to cut grooves at precisely half the depth of the specimen producing larger data scatter. Tearing in under cut specimens and bending and peeling in overcut ones were observed.

Short beam shear yields strengths, which are higher than slotted shear as well as torsion tube. But data may not be always reproducible.

• ITEM NO. 19

AUTHORS: Cron, S.M., Palazotto, A.N., and Sandhu, R.S.

TITLE: The Improvement of End Boundary Conditions For Off-Axis Tension Specimen Use

SOURCE: Exp. Mech., 28

pp: 14-19

DATE: 1988

TEST SPECIMENS: Off-axis

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: A rotating fixed grip arrangement is proposed and analyzed by finite element methods. It is suggested as an alternative to the use of large aspect ratio and long tapered tabs. Location of the specimen relative to the jaws of the grip, the position of the axis of rotation, can also be adjusted. These arrangements reduce stress peaks near specimen ends as evident from photoelastic observations. Failure occurs in the test section with the use of such fixtures.

• ITEM NO. 20

AUTHORS: Dastin, S., Lubin, G., Munyak, J., and Slobodzinski, A.

TITLE: Mechanical Properties and Test Techniques for Reinforced Plastic Laminates

SOURCE: ASTM STP 460

pp: 13-26

DATE: 1969

TEST SPECIMENS: Picture frame, Shear, Tension and Compression tests

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Reports that reliable shear modulus and strength can be obtained for fiber glass $(0/90)_s$ laminates using Picture frame shear test, but strain at high load levels are questionable.

Bow tie specimens are recommended for tension tests as compared to dogbone and straight-sided specimens.

• ITEM NO. 21

AUTHORS: Douglas, D.O., Holzmacher, D.E., Lane, Z.C., and Thornton, E.A.

TITLE: Studies in Finite Element Analysis of Composite material Structures

SOURCE: Old Dominion University Report 75-M3

pp: --

DATE: 1975

TEST SPECIMENS: Picture frame

CONTENTS:

Experimental Results? [Y/N] - N   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Corner stress concentrations are high as per finite element analyses including frame and nonlinear effects.

• ITEM NO. 22

AUTHORS: Duggan, M.F.

TITLE: An Experimental Evaluation of the Slotted-Tension Shear Test for Composite Materials

SOURCE: Exp. Mech., 20

pp: 233-239

DATE: 1980

TEST SPECIMENS: Slotted tension/compression, Rail shear, Double lap shear, ±45, Off-axis

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] -

REMARKS: Reports problems with rails slipping on the specimen in rail shear tests (under tension) requiring bolts to be retightened during tests. (The problem can be avoided by testing in compression and using bonded rails.)

Bonding is found to be a problem in double lap shear and thus strength can not be obtained. However, it may be possible to estimate interlaminar shear modulus from the normal strain at mid-plane along the sides of the specimen.

Finite element results of the slotted tension/compression (biaxial loading) presented in a previous work by the author (1978, item 53) are discussed. Modulus and strength for unidirectional Gr/Ep determined from this test are found to be higher than those from rail shear and ±45 tension test. Modulus from lap shear test is found to be close to that from slotted tension/compression method.

• ITEM NO. 23

AUTHORS: Duggan, M.F., McGrath, J.T., and Murphy, M.A.

TITLE: Shear Testing of Composite Materials by a Simple Combined Loading Technique

SOURCE: 19th SDM Conf., 78-508

pp: 311-319

DATE: 1978

TEST SPECIMENS: Cross beam, Slotted tension/compression

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Larger stresses in test section of cross beam specimen (as compared to simple theory) are reported.

Suggest a tensile specimen with two slots parallel to the load direction and a test section in between which is also subjected to compression on the sides of the test area. This creates a pure shear stress at 45° angles. Loading is complex. For (±45) laminate the stress state is found to be better than that in the cross beam even with the stress concentrations near the edge of the compression load pad. For (0/90) laminates failure occurred in tension which does not appear to be a valid failure mode. Biaxial loading for this specimen seems to be complicated.

*** ITEM NO. 24**

AUTHORS: Elkin, R.A., Fust, G., and Hanley, D.P.

TITLE: Characterization of Graphite Fiber/Resin Matrix Composites

SOURCE: ASTM STP 460

pp: 321-

DATE: 1969

TEST SPECIMENS: Slotted shear, Tension and Compression tests

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] -

REMARKS: Reports low shear strength values from slotted shear test attributed to stress concentration at the edge of slots or holes. A stress concentration factor of 1.57 is reported near slots as obtained from finite element analyses. Straight-sided tension specimens (3" wide for transverse tension test) and waisted compression specimens are suggested.

*** ITEM NO. 25**

AUTHORS: Farley, G.L. and Baker, D.J.

TITLE: In-Plane Shear Test of Thin Panels

SOURCE: Exp. Mech., 23

pp: 81-88

DATE: 1983

TEST SPECIMENS: Picture frame

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: In the fixtures used for metals, corner stresses are high. In a redesigned fixture chances of unanticipated failure modes like folding or crimping of the panel near corners under compression, and tearing due to tension along a diagonal or along the loading tab-panel interface, are reduced. Finite element analyses show that by placing corner pins at the corners of the panel (rather than at corners of load frame), the stress state is made more uniform and normal stresses are reduced. The stiffness of the loading tab (bonded to specimens) should be about 30 times that of the panel to obtain a reasonably acceptable stress distribution. Otherwise, bending (inplane) of the tab causes a non-uniform stress distribution at the corners. The distance from end of the loading tab to the nearest bolt used to transfer load from the fixture to the panel also plays a similar role. Good correlation between finite element analyses and measured strains near the central part of the panel are reported for buckling resistant panels. For obvious reasons, thin plates buckle and tensile failure occurs across a buckle as per classical diagonal tension theory. It appears that the fixtures on the specimen can be modified for testing of thin composites. However, the test appears to be a complicated one.

ITEM NO. 26

AUTHORS: Fieldman, A., Tasi, J., and Stang, D.A.

TITLE: Experimental Determination of Stiffness Properties of Thin Shell Composite Cylinders

SOURCE: Experimental Mech, 6

pp: 385-394

DATE: 1966

TEST SPECIMENS: Torsion tube

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Shear moduli of filament wound cylinders are obtained on the assumption of small thickness to diameter ratio and compared with analytical calculations.

*** ITEM NO. 27**

AUTHORS: Foley, G.A., Roylance, M.E., and Houghton, W.W.

TITLE: Use of Torsion Tubes to Measure In-Plane Shear Properties of Filament Wound Composites

SOURCE: ASTM STP 1003

pp: 208-223

DATE: 1989

TEST SPECIMENS: Torsion tube

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Reports results of torsion tests on filament wound tubes of ± 45 layups. Thin specimens (3 ply) are better for obtaining more uniform shear stress through the thickness but such specimens may buckle. 5 ply specimens appear to give reliable data. Suggest proper instrumentation to detect possible buckling failure. Possible microkinking of Kevlar is also suggested, but it may be a valid damage mode for ±45 layups of such materials.

• ITEM NO. 28

AUTHORS: Garcia, R., Weisshar, T.A., and McWhitney, R.R.

TITLE: An Experimental and Analytical Investigation of the Rail Shear Test Method as Applied to Composite Materials

SOURCE: Experimental Mech., 20

pp: 273-279

DATE: 1980

TEST SPECIMENS: Two rail shear

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Reports finite element analysis of and tests with rail shear specimens with uniform as well as tapered rails. Differences in the stress distributions between offset (diagonally) loaded and axially loaded (with appropriate end fixtures) specimens are less than 5% for quasi-isotropic laminates. Results for tapered rails are also similar except for the axial stress which are a little higher in the center. Aspect ratio has a significant influence on the stresses. Transverse stresses are high near the loaded corners and they are increased at higher temperatures due to thermal expansion. Stress-strain response of 0° and 90° (fibers perpendicular to rails) specimens shows that modulus, strength and ultimate strain from 0° material are lower, 90° specimens failing at twice the ultimate strain of 0°. The reason appears to be the high transverse stress which cause earlier failure of 0° specimens due to splitting. Test data from bonded rails show a stiffer response than bolted ones, the former method yielding acceptable data.

• ITEM NO. 29

AUTHORS: Greszczuk, L.B.

TITLE: Applications of Four Point Ring-Twist Test for Determining Shear Modulus of Filamentary Composites

SOURCE: ASTM STP 734

pp: 21-33

DATE: 1981

TEST SPECIMENS: Four point ring twist

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: The test is useful for shear modulus determination for rings, section of cylinder or a cone. Simple formulae are given for determining shear modulus from load deflection data.

*** ITEM NO. 30**

AUTHORS: Greszczuk, L.B.

TITLE: Shear Modulus Determination of Isotropic and Composite Materials

SOURCE: ASTM STP 460

pp: 140-149

DATE: 1969

TEST SPECIMENS: Plate twist, Split ring shear

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Large deflection of plates, warping (not perfectly flat), crushing at load points cause problems in plate twist tests. The specimen usually yields initial shear modulus only (based on small deflection theory). Torsion tube, off-axis and solid bar torsion tests are also reviewed.

Split ring shear test yields good data on shear modulus.

Test data for metal, unidirectional and bi-directional composite rings are presented.

*** ITEM NO. 31**

AUTHORS: Hadcock, R.N. and Whiteside, J.B.

TITLE: Special Problems Associated With Boron Epoxy Mechanical Test Specimens

SOURCE: ASTM STP 460

pp: 27-36

DATE: 1969

TEST SPECIMENS: Picture frame shear, Tension and Compression tests

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Reports high stress concentration at corners of picture frame specimen as per finite element analyses and tests on Boron/Epoxy and Borsic/Al specimens. The test is recommended only for material qualification and selection.

Modified straight-sided specimens with polished edges and long tabs as suggested for tension test.

*** ITEM NO. 32**

AUTHORS: Hahn, H.T.

TITLE: A Note on the Determination of the Shear Stress Strain Response of Unidirectional Composites

SOURCE: J. Comp. Mater, 7

pp: 383-386

DATE: 1973

TEST SPECIMENS: ±45

CONTENTS:

Experimental Results? [Y/N] - N   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Shows equivalence of Petit's and Rosen's results in absence of coupling between extensional and shear strains in a lamina. Such coupling is usually minimal, however. If the material is elastoplastic (metal matrix or thermoplastics) it may exist (not pointed out here) in some composites.

ITEM NO. 33

AUTHORS: Ho, H., Tasi, M.Y., Morton, J., and Farley, G

TITLE: A Comparison of Shear Test Methods for Composite Materials

SOURCE: Proc. ICCM VIII

pp: --

DATE: 1991

TEST SPECIMENS: Off-axis, ±45, Iosipescu

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Strain variations in the specimens obtained from Moire interferometry and strain gages are reported and compared. Shear stress-strain response from the three tests are compared before and after application of stress correction factors. It is seen that with this correction the responses are almost identical up to a strain level of 0.6%.

• ITEM NO. 34

AUTHORS: Ho, H., Tasi, M.Y., Morton, J., and Farley, G.L.

TITLE: An Evaluation of the Iosipescu Specimen for Composite Material Shear Property Measurement

SOURCE: VPI&SU Report CCMS-91-18

pp: --

DATE: 1991

TEST SPECIMENS: Iosipescu

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Finite element analyses and experimental studies are reported for 0°, 90° and (0/90) 90° and 110° rounded notch Iosipescu specimens. Use of correction factors is suggested. Pure shear strain (equal and opposite strains in ±45 directions) is not required to obtain valid test data. Twisting can play an important role in 90° and (0/90) specimens. Use of back-to-back gages is recommended. Soft shims may be utilized to reduce twisting effects. Ultimate stress levels from 90° specimens are thought to be low, but those from 0° and 0/90 specimens are not thought as representative material behavior, since values at first load drop are only reported.

ITEM NO. 35

AUTHORS: Hyer, M.W. and Douglas, D.O.

TITLE: A Comparison Between Experiment and Theory For A Borsic-Aluminum Picture Frame Shear Test

SOURCE: Old Dominion University Report 76-T18

pp: --

DATE: 1976

TEST SPECIMENS: Picture frame

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] -

REMARKS: Reports comparison of experimental data with analysis for panels with cutouts and/or doublers. Corner stresses are found to be high.

*** ITEM NO. 36**

AUTHORS: Ifju, P., and Post, D.

TITLE: A Compact Double-Notched Specimen for In-Plane Shear Testing

SOURCE: Proc. S.E.M. Conference, Cambridge, MA

pp:

DATE: May, 1989

TEST SPECIMENS: Compact double notched, Iosipescu

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: A compact specimen (notched) is used and the results compared with Iosipescu specimens for a crossply layup. Stress distribution is obtained using Moire interferometry. Shear stress distribution appears to be more uniform. Strength data are not reported. It is not clear how the load transfer fixture will perform at high loads.

*** ITEM NO. 37**

AUTHORS: Kadotani, K. and Aki, F.

TITLE: Analysis of the Interlaminar Shear Strength of Mica/Epoxy Insulations

SOURCE: Composites, 15

pp: 57-60

DATE: 1984

TEST SPECIMENS: Double lap shear, Short beam shear, Button torsion, Slant shear

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Reports results from different tests. Shear strengths obtained in decreasing order are short beam shear, button torsion and lap shear. Slant shear under compression yields data comparable to those from button torsion, strength being extrapolated for zero transverse compression load (since normal and shear stresses exist in this test). Under tension load failure occurs earlier. For zero transverse load the slant shear test is considered to be equivalent to lap shear. Stress concentration effect is recognized and it may be more critical for tensile loads.

*** ITEM NO. 38**

AUTHORS: Kellas, S., Morton, J., and Jackson, K.E.

TITLE: An Evaluation of the ±45 Tensile Test for the Determination of the In-Plane Shear Strength of Composite Materials.

SOURCE: Proc. ICCM VIII

pp:

DATE: 1991

TEST SPECIMENS: ±45

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Axial stress-strain response of $(\pm 45)_{ns}$ specimens with various widths and thicknesses (varying n) are reported. Stress-strain responses are found to differ with thickness, thinner ones failing early but the thicker ones (≥ 24 plies) reaching the strain-hardening (due to scissoring) range. Width (or edge effect) does not play a significant role unless the plies are arranged in blocks (as reported in item 27). The thickness effect is attributed to multiple ply cracks. Ply cracks start in the thickest ply at the center, but beyond the peak stress all the plies are cracked. Ply cracks appear to be more localized in thinner specimens.

It is suggested that calculation of shear stress as half the value of the laminate stress is correct provided the stress is uniform through the width and thickness of the specimen. This uniformity may not occur due to inhomogeneity (for example, existence of resin regions or creation of different extents of damage in the plies as load is increased). Scissoring effect may also contribute to incorrect estimates of shear stress in each ply. Use of thick specimens ($\geq$ 24 plies) is suggested which minimizes the chance of early failure due to ply cracks as well as high transverse stresses which are found to occur near the edges.

• ITEM NO. 39

AUTHORS: Kennedy, J.M., Barnett, T., and Farley, G.L.

TITLE: Analysis of the Picture Frame In-Plane Shear Test For Composite Materials

SOURCE: AIAA/ASME/ASCE/AHS 28th SDM Conference

pp: 402-407

DATE: 1987

TEST SPECIMENS: Picture frame shear

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Stress distributions were calculated using 2-D and 3-D finite elements for (0/90) and ($\pm$45) layups. Normal stresses are negligible at the center of test section, but not at the corners, where the stresses become small only when ratio of doubler stiffness to that of specimen increases. Shear stress at the center decreases and reaches an asymptotic limit as the stiffness ratio increases. It is difficult to achieve the high stiffness ratio required for ideal stress distribution. In its present form the test method is not recommended for use, since the shear moduli obtained are low and it is inappropriate to determine strength.

• ITEM NO. 40

AUTHORS: Lee, S., and Munroe, M.

TITLE: Evaluation of In-Plane Shear Test Methods for Advanced Composite Materials by the Decision Analysis Technique

SOURCE: Composites, 17

pp: 13-20

DATE: 1986

TEST SPECIMENS: Rail shear, ±45, Off-axis, Cross beam, Picture frame, Torsion tube, Slotted tension, Iosipescu

CONTENTS:

Experimental Results? [Y/N] - N Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Excellent review of all test methods. Rates methods based on weighing for various factors like cost of fabrication and testing, reproducibility and accuracy. Iosipescu and ±45 are rated highest in the list. Gives a good discussion of accuracy of various methods as reported in literature and torsion tube is considered to be the most accurate method. Iosipescu, ±45 and off-axis and rail shear tests are judged as comparable to Torsion Tube from the point of view of accuracy.

• ITEM NO. 41

AUTHORS: Lee, S. and Munroe, M.

TITLE: Evaluation of Testing Techniques for the Iosipescu Shear Test for Advanced Composite Materials

SOURCE: J. Comp. Mater., Vol. 24

pp: 419-440

DATE: 1990

TEST SPECIMENS: Iosipescu

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] -

REMARKS: Examines use of original University of Wyoming fixture for 90° and 0° specimens. The main conclusions are given below.

Good quality machined notches can be produced with proper care. Tensile and compressive strains should be monitored to check for pure shear strain in gage section which can be produced in 90° specimens. 0° specimens do not have a state of pure shear in gage section, which is attributed to proximity of loading points. The placing of specimen in the original fixture requires care. All loading faces should be ground and parallel. Use of proper shims is also suggested. Modified Wyoming fixture with adjustable loading faces is better, but care as described above is still needed to reduce bending and twisting.

<u>ITEM NO. 42</u>

AUTHORS: Lenoe, E.M.

TITLE: Testing and Design of Advanced Composite Materials

SOURCE: J. Eng. Mech. Div., ASCE

pp: 809-823

DATE: 1970

TEST SPECIMENS: Cross-beam, Torsion tube

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Reports that shear strength from cross beam shear to be 30% lower than that from torsion tube.

*** ITEM NO. 43**

AUTHORS: Lenoe, E.M., Knight, M., and Schoene, C.

TITLE: Preliminary Evaluation of Test Standards for Boron Epoxy Laminates

SOURCE: ASTM STP 460

pp: 122-139

DATE: 1969

TEST SPECIMENS: Short beam shear, Torsion of rod, Tension, Compression and Flexure tests

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Width and span-to-depth ratio effects on short beam shear test data are discussed along with torsion test data. Specimens need to be examined for true shear failure mode.

Some studies on influences of tab materials, bondline, strain rate and width on tension tests are reported.

*** ITEM NO. 44**

AUTHORS: Lewis, E.Q., and Adams, D.F.

TITLE: An Evaluation of Composite Material Shear Test Methods

SOURCE: University Of Wyoming Report UW-CMRG-R-91-103

pp:

DATE: May, 1991

TEST SPECIMENS: Iosipescu, Rail shear, Short beam shear, $(\pm 45)_{ns}$ Tension

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: 0° and 90° Iosipescu, Two rail shear, $(\pm 45)_{ns}$ tension, and Four Point Beam Shear Test Methods are investigated experimentally for glass and graphite fiber reinforced thermosets and thermoplastics. Differences in results are discussed in detail with reference to failure mechanisms. In addition, some results from a special Iosipescu specimen called the flat bottom notch are also presented.

*** ITEM NO. 45**

AUTHORS: Lockwood, P.A.

TITLE: Results of the ASTM Round Robin on the Rail Shear Test for Composites

SOURCE: Composite Technol. Rev., 3

pp: 83-86

DATE: Summer, 1981

TEST SPECIMENS: Two and three rail shear

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Reports results of ASTM round robin. Too much variability in results (possibly for variability in materials, peculiar stress states and possibility of constrained or unconstrained damage growth from the loaded corners not discussed in this work, but identified in others, see, for example, item 23). For this reason the test method was documented as an ASTM Guide, not a standard. Two and three rail system give similar results.

*** ITEM NO. 46**

AUTHORS: Markham, M.F. and Dawson, D.

TITLE: Interlaminar Shear Strength of Fiber Reinforced Composites

SOURCE: Composites, 6

pp: 173-176

DATE: 1975

TEST SPECIMENS: Slotted shear

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: A simple strength of materials type analysis is given for shear stress distribution between the slots.

Load application is not a problem.

Shear stress distribution between slots may not be uniform.

Failure is always in a plane and consistent results are obtained for different lengths between slots (it appears, however, this consistency may be due to the curve fitting procedure employed).

Tests for different lengths are required to obtain required data on strength.

*** ITEM NO. 47**

AUTHORS: Marloff, R.H.

TITLE: Finite Element Analysis of Bi-Axial Stress Test Specimen for Graphite/Epoxy and Glass Fabric/Epoxy Composites

SOURCE: ASTM STP 787

pp: 34-49

DATE: 1982

TEST SPECIMENS: Arcan

CONTENTS:

Experimental Results? [Y/N] - Y　　　Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: End effects not studied, but it is pointed out that failure can often occur away from gage section. Reinforcements are needed to prevent such failures.

Shear stress is fairly uniform in the gauge section for fabric (Gl/Ep) but not for unidirectional Gr/Ep. Stresses are higher at the boundary (near the notch). For Gr/Ep the fibers are parallel to test cross section and hence it corresponds to a 90° Iosipescu type specimen (hence stress variations are similar to later specimens). Other stresses also exist.

Failure usually occurs slightly away from gage section possibly due to high stresses at the boundary as well as effect of transverse stress. For this reason modulus data appear all right but strengths are possibly lower than expected.

Data analysis is simple, but the fixture is complicated and is similar to Iosipescu specimen studied by Bergner, Davis and Herakovich.

<u>**ITEM NO. 48**</u>

AUTHORS: Munjal, A.K.

TITLE: Test Methods for Determining Design Allowables for Fiber Reinforced Composites

SOURCE: ASTM STP 1003

pp: 93-110

DATE: 1989

TEST SPECIMENS: Various Methods

CONTENTS:

Experimental Results? [Y/N] - N　　　Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Excellent review of factors affecting composite properties, cares needed in specimen fabrication and preparation and test methods. Iosipescu, torsion tube and ±45 and rail shear tests are recommended for inplane shear. Iosipescu is suggested for interlaminar shear. Four point short beam shear is pointed out as a method which gives good strength data but needs further development.

*** ITEM NO. 49**

AUTHORS: Nemoth, M.P., Herakovich, C.T., and Post, D.

TITLE: On the Off-Axis Test for Unidirectional Composites

SOURCE: Composite Tech. Review, 5, No. 2

pp: 61-68

DATE: 1983

TEST SPECIMENS: Off-axis

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Large aspect ratio (length/width ≈ 15) is required to reduce end effects. Complex biaxial stress states at one of the corners of the specimen. Good correlation is reported between finite element and Moire interferometry results.

*** ITEM NO. 50**

AUTHORS: Pagano, N.J., and Whitney, J.M.

TITLE: Geometric Design of Composite Cylindrical Characterization Specimens

SOURCE: J. Comp. Mater., 4

pp: 360-378

DATE: 1970

TEST SPECIMENS: Torsion tube

CONTENTS:

Experimental Results? [Y/N] - N Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Analytical study of stress fields in torsion tube for balanced symmetric and helically wound cylinders with idealized end conditions.

End effects decay quickly. Suggest length = 4 times radius + gage length. But smaller dimension may be suitable.

Stress state shows minor variation through the thickness for large radius to thickness ratio and therefore appear to be ideal.

• ITEM NO. 51

AUTHORS: Peters, P.W.M.

TITLE: The Interlaminar Shear Strength of Unidirectional Boron Aluminum Composites

SOURCE: J. Comp. Mater., 12

pp: 53-62

DATE: 1978

TEST SPECIMENS: Short beam shear, Symmetric block shear

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Test results are presented and discussed. It is argued that in materials with matrix materials which can undergo large plastic deformation, short beam shear can cause rupture of the fibers (due to flexure) before shear failure. In addition, non-parabolic shear stress distribution (almost uniform due to plastic flow) may cause the shear strength to be overestimated. On the other hand, resistance exerted on parts of the specimen that are pushed into the fixture may cause some increase in failure load (10-15%) in block shear test.

*** ITEM NO.** 52

AUTHORS: Petit, P.H.

TITLE: A Simplified Method of Determining the In-Plane Shear Stress-Strain Response of Unidirectional Composites

SOURCE: ASTM STP 460

pp: 83-93

DATE: 1969

TEST SPECIMENS: (±45), Cross beam

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: First use of (±45) test showing the promise of such tests.

Discusses possible edge delaminations at high strains (boron epoxy data given up to 4.5% shear strain level).

Stress state all right except near edges.

Data analysis in the form given was complicated. Good comparison with cross beam except at high strains.

*** ITEM NO.** 53

AUTHORS: Phillips, D.C. and Scott, J.M.

TITLE: The Shear Fatigue of Unidirectional Composites

SOURCE: Composites, 8

pp: 233-236

DATE: 1977

TEST SPECIMENS: Short beam shear, Torsion of solid bar

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Torsion test is thought to be more reliable than short beam shear, the latter being influenced by non-uniform stress states, combined stresses and severe stress concentrations. Machining of square rods to produce a test section with an aspect ratio (length/diameter) of about 16, but leaving the ends to be square with sides equal to the diameter of the test area, is suggested. Nonlinear torque twist responses are reported for Gr/Ep and Gl/Ep. Shear strengths from short beam shear are found to be higher than those from torsion test. Macroscopic crack growth is found to occur in torsion fatigue tests after an initial growth of microdamages.

ITEM NO. 54

AUTHORS: Pindera, M.J.

TITLE: Shear Testing of Metal Matrix Composites

SOURCE: ASTM STP 1032

pp: --

DATE: 1989

TEST SPECIMENS: Off-axis, Iosipescu

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: It is shown that fiber misalignment and strain gage alignment are of importance, the former being of significance for small off-axis angles like 10°-15°. End effects in off-axis tests and non-uniform stress distribution in Iosipescu specimens are accounted for by the use of analysis as described in previous works by the author. Results of tests (0° and 90°

Iosipescu and various off-axis tests) are found to yield similar modulus for epoxy and metal matrix composites with fine microstructure if corrections are employed. However, for Boron/Al with large diameter fibers, Iosipescu tests yield lower modulus as compared to 10° off-axis data and analytical results. Reasons for these observations are not clear but presence of high stress gradient and large diameter fibers in a small gage section are possibly not desirable.

ITEM NO. 55

AUTHORS: Pindera, M.J., Choksi, G., Hidde, J.S., and Herakovich, C.T.

TITLE: A Methodology for Accurate Shear Characterization of Unidirectional Composites

SOURCE: J. Comp. Mater., 21

pp: 1164-1184

DATE: 1987

TEST SPECIMENS: Off-axis, Iosipescu

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Finite element results for 110° rounded notch Iosipescu specimens yield the correction factors in shear stress for determining the modulus. For 10° off-axis tests, a correction factor ($\approx$ 0.94) is required even for an aspect ratio (L/W) of 16 in aramid/epoxy materials. For 45° off-axis, no correction is required for an aspect ratio of 10. But due to high transverse tension, failure occurs early in 45° off-axis tests. 90° Iosipescu strengths (or ultimate strains) are higher than 45° off-axis data, but lower than those from 10° off-axis test for Ar/Ep. 0° Iosipescu ultimate strength and strain are much higher than other data for Ar/Ep, but for Gr/polymide, it is less than 10° off-axis with large end constraint (low L/W). Corrections required for the aspect ratio effect in the off-axis test are taken from a previous work by the same authors. Those required in Iosipescu specimens are given in graphical form. Failure mechanisms discussed are similar to those obtained in other studies. It is suggested that the response of 0° Iosipescu specimen after axial splitting is influenced by structural rather than material response, but 90° Iosipescu strengths are low.

*** ITEM NO. 56**

AUTHORS: Pindera, M.J. and Herakovich, C.T.

TITLE: Shear Characterization of Unidirectional Composites With the Off-Axis Tension Test

SOURCE: Exp. Mech., 26

pp: 103-112

DATE: 1986

TEST SPECIMENS: Off-axis

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Reports correction factors and shear stress-strain response for off-axis tests with different angles. Based on a finite element study by Rizzo (J. Comp. Mater., 3, 1969, p. 202), a rotating fixed grip arrangement is used in tests, to reduce end constraint effects and obtain gage section failures. A similar arrangement is suggested by Cron, Palazotto and Sandhu (SEM Spring Conf. Proc., 1986, p. 343).

*** ITEM NO. 57**

AUTHORS: Ramnath, V., and Chatterjee, S.N.

TITLE: Composite Specimen Design Analysis

SOURCE: MSC TFR 1701/1703, AMTL Contract DAAG 46-85-C-0058

pp:

DATE: 1986

TEST SPECIMENS: ±45, Torsion of rectangular bar, Iosipescu, Two rail shear

CONTENTS:

Experimental Results? [Y/N] - N   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: ($\pm$45) Tension

Edge delaminations may occur but should not be critical by themselves. Width > 1/2" suggested. Results based on fracture mechanics analyses.

Transverse tensile stresses exist in the layers. Its magnitude decreases with increase in the ratio of longitudinal to transverse Young's moduli of the layers. Thus, tensile stress in Gr/Ep will be less than that in Gl/Ep, but later material has been found to fail at higher shear strain than the former (see item 20).

Dispersed transverse cracks with or without delaminations may not be critical as per fracture mechanics analysis. However, generation of closely spaced ply cracks and delaminations as well as possible interaction with edge delaminations may cause early failure [see item 23]. This phenomenon has not been studied. However, dispersed lay-up (no lumping) will yield higher failure stresses and strains.

Other Tests

Results summarized in next item.

<u>* ITEM NO.</u> <u>58</u>

AUTHORS: Rizzo, R.R., and Vicario, A.A.

TITLE: A Finite Element Analysis for Stress Distribution in Gripped Tubular Specimens

SOURCE: ASTM STP 497

pp: 68-88

DATE: 1972

TEST SPECIMENS: Torsion tube

CONTENTS:

Experimental Results? [Y/N] - N   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Study of stress fields near end grips (internal and external).

Stresses near grips are high (possibly lower than tabbed case) but decay quickly and may not cause early failure because of stress redistribution. Length to diameter ratio greater than 3 is suggested.

Stress state similar to that found in Pagano and Whitney's work (J. Comp. Mater., 4, 1970, pp. 360-378) and Whitney and Halpin's analyses (J. Comp. Mater., 2, 1968, pp. 360-367). Thickness to diameter ratio less than .05 is recommended.

• ITEM NO. 59

AUTHORS: Rosen, B.W.

TITLE: A Simple Procedure for Experimental Determination of the Longitudinal Shear Modulus of Unidirectional Composites

SOURCE: J. Comp. Mater., 6

pp: 552-554

DATE: 1972

TEST SPECIMENS: (±45)

CONTENTS:

Experimental Results? [Y/N] - N   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: No study of end effects. Careful study and consideration of free edge effects suggested for choice of specimen width.

Stress state uniform in each layer over a large area, but transverse stress exist and may influence response.

No information in failure mode

Simple data reduction procedure is described.

ITEM NO. 60

AUTHORS: Rothman, E.A., and Molter, G.E.

TITLE: Characterization of the Mechanical Properties of a Unidirectional Carbon Fiber Reinforced Epoxy Matrix Composite

SOURCE: ASTM STP 460

pp: 72-82

DATE: 1969

TEST SPECIMENS: Short beam shear, Plate twist, Dynamic torsion, Tension and Flexure tests

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Short beam shear does not produce shear failures consistently and, therefore, data may be accepted only when shear failure occurs. Load deflection equation used in plate twist test is not correct. Dynamic modulus (torsion and flexure) measurement is possible and shows promise. Dogbone tension specimen should be modified (geometry) depending on the ratio of tensile and shear strength.

• ITEM NO. 61

AUTHORS: Sandhu, R.S. and Sendeckyj, G.P.

TITLE: On Design of Off-Axis Specimens

SOURCE: AFWAL-TR-84-3098

pp:

DATE: 1985

TEST SPECIMENS: Off-axis

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Reviews past works by Tasi, Lauritis, Pagano and Halpin, Rizzo, Wu and Thomas, and Cole and Pipes on off-axis specimens (not necessarily for shear characterization). These works deal with specimen modifications (dogbone type to produce failure in gage section), end constraints due to clamping, rotating end grips and use of highly tapered end tabs with fiber orientation same as that of the specimen. Effects of bevelled square ended and inclined (making an angle $\neq 90°$ to specimen axis) 0/90 scotch ply tabs used in conjunction with rotating grips are studied. It was found that the tabs can be designed to reduce end constrain effects.

Nonlinear analyses are performed for specimens with different off-axis angles which are correlated with test data. Off-axis angles can be chosen either to maximize shear stress or minimize transverse stress (not simultaneously). For 10° off-axis test, transverse stress is found to have a significant influence on failure based on an assumed failure criterion. Contribution of shear stress to failure can also be optimized and some results of this process are reported based on linear as well as nonlinear theories. Test data (stress-strain response) for fixed off-axis angle show some scatter, which can be reduced by measuring the deviation of this angle in test specimens. However, some scatter remains and because of this fact, no experimental validity can be shown for improvements due to inclined tab ends as observed analytically.

*** ITEM NO. 62**

AUTHORS: Sattar, S.A. and Kellogg, D.H.

TITLE: The Effect of Geometry on the Mode of Failure of Composites in the Short Beam Shear Test

SOURCE: ASTM STP 460

pp: 62-71

DATE: 1969

TEST SPECIMENS: Short beam shear

CONTENTS:

Experimental Results? [Y/N] - N Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Investigates effects of geometry on failure modes. Failures due to tensile, compressive and interlaminar shear stresses are studied for various span-to-depth ratio. Correction factors are given for various width to depth ratios.

*** ITEM NO. 63**

AUTHORS: Sims, D.F.

TITLE: In-Plane Shear Stress Strain Response of Unidirectional Composite Materials

SOURCE: J. Comp. Mater, 7

pp: 124-128

DATE: 1973

TEST SPECIMENS: Three rail shear, ±45, Torsion tube

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: Good comparison of results for glass/epoxy $(0/90)_{2s}$ rail shear and $(\pm 45)_{2s}$ tension up to a strain level of 4%. Also $(\pm 45)_{2s}$ data for graphite/epoxy compared with torsion tube data and $(\pm 45)_s$ data from Southwest Research Institute. Torsion with fibers parallel to longitudinal axis of tube sustain very high strain levels (>4.5%) compared to ±45 specimens (≈ 2 to 3%).

No discussions on end/edge effects or failure mode.

*** ITEM NO. 64**

AUTHORS: Sleepetz, J.M., Zageski, T.F., and Novello, R.F.

TITLE: In-Plane Shear Test for Composite Materials

SOURCE: AMMRC TE 78-30

pp:

DATE: 1978

TEST SPECIMENS: Asymmetric four point bend

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: The bend test without and with notches (similar to Iosipescu with prescribed load instead of displacements) is considered. Finite element analyses as well as experimental investigations with strain gages and Moire technique are reported.

Frictional effects at load points are pointed out as undesirable.

Stress state is acceptable for notched specimens with fillet. Shear stress is more or less uniform, other stresses are small in next section.

In unidirectional graphite/epoxy, failure mode is usually shear dominated (high ultimate strains). Notch root failures like those discussed in studies of Iosipescu specimens occur to yield load drops.

Data reduction is simple.

Cross-ply specimens appear to yield better results and very high ultimate loads and strains.

*** ITEM NO. 65**

AUTHORS: Stinchcomb, W.W., Henneke, E.G., and Price, H.L.

TITLE: Use of the Short Beam Shear Test for Quality Control of Graphite Polymide Laminates

SOURCE: ASTM STP 626

pp: 96-

DATE: 1977

TEST SPECIMENS: Short beam shear

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: It is observed that the failure mode is a combination of shear and microbuckling or microbuckling alone. Shear failure occurs only when there are severe defects or poor quality bonding.

*** ITEM NO. 66**

AUTHORS: Sumsion, H.T. and Rajapakse, Y.D.S.

TITLE: Simple Torsion Test for Determining The Shear Moduli of Orthotropic Composites

SOURCE: Comp. Tech. Rev., 1

pp: 8

DATE: 1979

TEST SPECIMENS: Torsion of rectangular bar

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Reports ways to determine shear modulus from torsion test on rectangular bars

*** ITEM NO. 67**

AUTHORS: Sun, C.T. and Berreth, S.P.

TITLE: A New End Tab Design For Off-Axis Tension Test of Composite Materials

SOURCE: Purdue Univ. HTMIAC Report 5

pp:

DATE: 1987

TEST SPECIMENS: Off-axis

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: A new end tab fabricated of fiber glass knit and a compliant silicone rubber matrix is shown to reduce end constraint effects even with clamped hydraulic grips and short specimens. An aspect ratio (L/W) of 4 is found to yield good results. Use of a strength criterion is suggested to determine the shear strength in presence of transverse and axial stresses.

• ITEM NO. 68

AUTHORS: Swanson, S.R., Messick, M., and Toombes, C.R.

TITLE: Comparison of Torsion Tube and Iosipescu In-Plane Shear Test Results for a Carbon Fiber Reinforced Epoxy Composite

SOURCE: Composites, 16

pp: 220-224

DATE: 1985

TEST SPECIMENS: Torsion tube, Iosipescu

CONTENTS:

Experimental Results? [Y/N] - Y Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Torsion of tubes with fibers in hoop direction yields response similar to Iosipescu up to a shear strain of 1.5%

Torsion Tube

No discussion of end effects or stress state

Failure occurs early at $\gamma \approx 2.5\%$ because of possible unconstrained crack growth in hoop wound cylinders away from grips.

Iosipescu

No discussion of end effects or stress states

Shows stiffer response beyond $\gamma \approx 1.5\%$, but load drops noticed because of cracks at notches. Constrains on crack growth (attributed to fiber orientation) and large rotation are given as reasons for failure at very high strain levels ($\approx$ 6%).

*** ITEM NO.** 69

AUTHORS: Swanson, S.R., Toombes, G.R., and Beckwith, S.W.

TITLE: In-Plane Shear Properties of Composites Using Torsion Tests of Thin Walled Tubes

SOURCE: Proc. 29th Natl. SAMPE Symposium

pp: 567-577

DATE: 1984

TEST SPECIMENS: Torsion tube

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Torsion of hoop wound tubes yield reliable modulus and strength (strength of pure hoop wound tubes may below as discussed in other items).

*** ITEM NO. 70**

AUTHORS: Terry, G.

TITLE: A Comparative Investigation of Some Methods of Unidirectional, In-Plane Shear Characterization of Composite Materials

SOURCE: Composites, 10

pp: 233-237

DATE: 1979

TEST SPECIMENS: Picture frame, Two rail shear, ±45, Plate twist, Short beam shear

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: 0° and (0/90) picture frame shear, (0/90) rail shear and ±45 show similar responses up to a shear strain level of 2.5%. Initial modulus from plate twist also compares well with others. Shear strengths (and ultimate strains) differ widely, (0/90) rail shear value being the highest (124 MPa) and (±45) with lumped layers being the lowest (58 MPa). Short beam shear, (±45) (dispersed layers) and 0° picture frame lie in between. Different mechanisms of failure are given as reasons for the difference in strength. Constraints imposed on ply crack growth (highest in 0/90 rail shear and lowest in ±45 (lumped layers)) are possibly the main reasons for the difference (not discussed). Suggests use of 2% as a strain limit to prevent matrix crazing. Below this value most of the tests give similar results.

*** ITEM NO. 71**

AUTHORS: Waddoups, M.E.

TITLE: Characterization and Design of Composite Materials

SOURCE: Composite Mtl. Workshop, Technomic

pp: 254-308

DATE: 1968

TEST SPECIMENS: Cross beam, Short beam shear

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - N

REMARKS: (0/90) cross beam shear strength is found to be much higher than 0° short beam shear. This is expected because of inherent strengthening of (0/90) in inplane shear due to fiber rotations after initial fracture and the flexure effects in short beam. Further short beam yields interlaminar shear strength.

*** ITEM NO. 72**

AUTHORS: Walrath, D.E. and Adams, D.F.

TITLE: Verification and Application of the Iosipescu Shear Test Method

SOURCE: Univ. of Wyoming UWMB-DR-401-103-1

pp:

DATE: 1984

TEST SPECIMENS: Iosipescu - Inplane and Interlaminar

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - Y

REMARKS: Effects of various modifications of the University of Wyoming fixture are studied and details of fixtures required are given.

Finite element analyses of specimens with rounded notches, varying notch angles, larger specimens and increasing the distance of load points from test section show acceptable stress distribution. A notch angle of 100° (or 120° as used in a previous study) and larger specimens (0.75" x 3") yield good results for unidirectional and fabric composites. Elasto-plastic material behavior and/or cracks at notch root (in unidirectional composites) do not affect the results significantly.

Initial cracking (in unidirectional materials) at notch roots occurs yielding some load drops, but is not critical. Crushing failures may occur under loads but may be avoided by increasing notch depth, tabbing the ends of the specimens, testing (0/90) layups and/or changing the fixture loading surface shape.

Testing of woven composites show local re-orientation of fibers after initial shear failures.

The test is also shown to be a good one (possibly the best available at this time) for interlaminar shear. However, a sufficiently thick specimen has to be prepared by stacking the layers of a particular material. Alternatively, they can be stacked to produce a long specimen.

ITEM NO. 73

AUTHORS: Whitney, J.M.

TITLE: Elasticity Analysis of Orthotropic Beams Under Concentrated Loads

SOURCE: Composites Sci. and Technology

pp: 167-184

DATE: 1985

TEST SPECIMENS: Short Beam Shear

CONTENTS:

Experimental Results? [Y/N] - N   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Reports stress analysis in beams with various span-to-depth ratios showing differences from beam theory. Discusses possible effects on failure. Both three-point and four-point loaded beams are studied.

***ITEM NO. 74**

AUTHORS: Whitney, J.M., and Halpin, J.C.

TITLE: Analysis of Laminated Anisotropic Tubes Under Combined Loading

SOURCE: J. Comp. Mater., 2

pp: 360-367

DATE: 1968

TEST SPECIMENS: Torsion tube

CONTENTS:

Experimental Results? [Y/N] - N   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Deals with application of thin shell theory to laminated tubes under general loading including torsion.

<u>ITEM NO. 75</u>

AUTHORS: Whitney, J.M., Stansbarger, D.L., and Howell, H.B.

TITLE: Analysis of Rail Shear Test-Applications and Limitations

SOURCE: J. Comp., Mater, 5

pp: 24-34

DATE: 1971

TEST SPECIMENS: Two rail shear

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - Y

Failure Mode Info? [Y/N] - N

REMARKS: Reports stress analyses of laminate specimens with rigid rails and length to width ratio = 12.

Stress distribution shows nonuniformity near ends -- high stresses at corners.

Average shear stresses equal those obtained a little distance away from ends for (0/±45) layup, but not for layups with high Poisson's ratio as in (±45). Limited test data.

ITEM NO. 76

AUTHORS: Yeow, Y.T., and Brinson, H.F.

TITLE: A Comparison of Simple Shear Characterization Methods for Composite Laminates

SOURCE: Composites, 9

pp: 49-55

DATE: 1978

TEST SPECIMENS: Off-axis, ±45, Three rail shear

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: Compares results for different specimens for T300/934 Gr/Ep. ±45 and (0/90) rail shear compare well till 4.5% strain level (when ±45 fails). Rail shear data given to 8% strain. 0° rail shear show large scatter. ±45 and (0/90) rail shear specimens show extensive interply failures as well as delaminations, which are suspected as reasons for compliant behavior as compared to off-axis test which fail in a brittle fashion between fibers (at about 2% strain level. However, end effects in off-axis tests (no correction factor as discussed in other recent works) are not considered.

*** ITEM NO. 77**

AUTHORS: Zabora, R.F. and Bell, J.E.

TITLE: A Test Technique to Study Interlaminar Shear Phenomena of Laminated Composites

SOURCE: AFFDL-TR-71-67

pp: --

DATE: 1971

TEST SPECIMENS: Single block shear

CONTENTS:

Experimental Results? [Y/N] - Y   Analytical Results? [Y/N] - N

Failure Mode Info? [Y/N] - Y

REMARKS: End bearing compressive strength in composites is low and crushing may occur. Block shear also does not produce a state of pure shear. Eccentric loads may produce localized normal loading on shear plane.

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