158
96

A STUDY OF TENSION, COMPRESSION, AND SHEAR TEST METHODS FOR ADVANCED COMPOSITES

by

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(ABSTRACT)

A study of the literature pertaining to test methods for advanced composite materials has been carried out. Several test methods were discussed and compared for each of three areas of interest. These areas were uniaxial tension, uniaxial compression and in-plane shear. Test methods were selected for tension, compression and shear and guidelines set for the entry of material property data into a comprehensive mechanical property database being undertaken by Virginia Tech's Center for Composite Materials and Structures (CCMS). According to the findings, recommendations for future work were made.

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LIST OF ABBREVIATIONS

AFPB	Antisymmetric Four Point Bend test.
ASTM	American Society for Testing and Materials.
CCMS	Virginia Tech's Center for Composite Materials and Structures
CRAG	Composites Research Advisory Group.
IITRI	Illinois Institute of Technology Research Institute.
MIL HDBK 17	Military Handbook 17.
SACMA	Suppliers of Advanced Composite Materials Association.
SRM	SACMA Recommended Method.
WF2	modified Wyoming Fixture.

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

A composite is any material composed of two or more constituents and which has some property (eg mechanical) that is more desirable than the corresponding property of either component alone. This broad definition includes wood, reinforced concrete, fiberglass, and many other materials. The scope of this project was focused specifically on certain advanced composites, which are composites employing a fibrous, high strength and stiffness material, incorporated a matrix material. The matrix could be a polymer, metal, or ceramic. The area of advanced composites is growing ever larger because of the unique advantages they offer the aerospace, transportation and marine industries. Structural composites offer very high strength-to-weight and stiffness-to-weight ratios. Because many composites are better thermal insulators and dampen vibration, they can decrease the weight added for additional insulation and attenuators in aircraft and other vehicles. Composites also have very good fatigue characteristics when compared with aluminum alloys and other metals. One of the biggest advantages of composites stems from their anisotropic nature. Since laminated composites have different material properties depending on the lamination sequence, they can be tailored to suit a given structural application.

The number of fiber/matrix systems has vastly increased as new materials are being used. Metal matrix composites are of particular interest because of their increased operating temperatures and their ductility. However, at this time, metal matrix composites are difficult to manufacture and process, and data are not readily available for their mechanical properties.

With recent interest in very high temperature composites, ceramic matrix composites are now being studied extensively. Ceramic matrix composites offer improved service temperatures (1000-1500 °C), but they tend to be very brittle at room temperature. Such materials are best suited to very high temperature applications such as turbine blades and heat shields for re-entry vehicles.

Metal and ceramic matrix composites are generally used in classified engineering projects. Therefore, there is only limited information about these materials, and hence the scope of this research was restricted to continuous, high-modulus fibers in polymer matrices. See Figure 1 [1]. These are the most common composite materials and are those that are best understood and characterized. Throughout the rest of this report, the words composite materials and composites will refer to this specific class of materials.

In order to further define the scope of the project, only laminated composites were studied. Filament winding, pultrusion, resin transfer molding, etc. are important manufacturing processes, but at present, lamination is the most common process for manufacturing advanced composite structures.

Since laminates are to be discussed, it is necessary to define the terms used to describe a laminated structure. A lamina or ply is a layer of composite with unidirectional fiber orientation. It may be of any thickness and in practice may consist of more than one layer as long as all of the fibers are in the same direction. A laminate is a structure composed of more than one ply. In a laminate, the fibers in a given ply are oriented in some specified direction. The sequential listing of the angles that the fibers in each ply make with some reference axis is referred to as the stacking sequence.

1.1. COMPOSITE MECHANICAL PROPERTIES

When discussing any material, it is necessary to know what properties are of interest. This work focuses specifically on the mechanical properties of composites. Such properties include the uniaxial stiffness and strength in both tension and compression, and the shear stiffness and strength.

1.1.1 Ply Properties

The principal material directions of a single composite ply are defined in Figure 2a. Direction 1 is parallel to the fibers, 2 is transverse to the fibers in the plane of the lamina, and 3 is transverse to the fibers and perpendicular to the 1-2 plane. Consequently, E_i, G_{ij}, S_i, S_{ij}, refer to stiffness and strength with the subscript indicating a direction or plane.

1.1.2 Laminate Properties

The laminate mechanical properties are the properties of a laminated structure made of two or more plies. Figure 2b defines the global directions of a laminate. The x-, y- and z-directions are the laminate principal directions in which loads are usually applied. The fibers in each ply within the laminate will be oriented at some angle ϕ to the x-direction, with ϕ being referred to as the stacking sequence angle. The stiffness and strength for a given staking sequence can be either determined directly through testing, or can be predicted from more basic quantities, such as ply properties. In prediction of stiffness, classical lamination theory is commonly used because of its ease of application. Classical lamination theory is, however, a 2-D theory and does not take into account 3-D phenomena such as edge effects [2] or scaling [3].

The strength of the laminate can be predicted by the use of some failure criterion, such as the Tsai-Hill or quadratic criteria [2], coupled with a ply discount procedure to account for accumulated damage. Predicting laminate strengths from ply strengths is not a recommended practice for design, but it can be useful as a first approximation. A more accurate method of predicting laminate strength involves the combined use of both ply properties and certain sublaminate properties. If, in addition to the ply properties, the properties of a basic sublaminate, such as ±45° are known, the accuracy of the resulting strength prediction of, say, a $[0°/+45°/-45°/90°]_S$ laminate can be improved significantly [4].

1.2. UNIQUE CHARACTERISTICS

Composite materials exhibit very different mechanics than do most other engineering materials. Composites are anisotropic, non-linear in their stress-strain response and can be bimodular. The added complexity of composites' anisotropic nature means that much more analysis must go into a design. However, anisotropy offers the designer opportunities that do not exist with isotropic materials.

1.2.1 Coupling

In the most general layup, there are several types of mechanical coupling that occur [2]. Coupling is present if when a structural element is loaded in one mode (say axially), it responds in some other mode (say shear) in addition to the expected mode. The three basic types of coupling are as follows:

1. Shear/extension
2. Bend/extension
3. Bend/twist

Coupling must be taken into account if one is to predict the mechanical response of a composite structure. Even though it makes the design process of a composite structures more complex, coupling can be used advantageously to optimize a design. One well-known example of this is the X-29 demonstrator aircraft. Taking advantage of the bend/twist coupling effect, the composite skin for the X-29's forward-swept wing was designed such that it has a built-in aerodynamic and structural stability. This design could only have been realized through the use of composite materials.

1.2.2 Non-Linearities

Like many materials, composites tend to have non-linear stress/strain relations. However, unlike other materials, the stiffness of a unidirectional tensile specimen is pulled in the 1-direction may increase with increased strain. This behavior may be reversed in compression [5]. See Figure 3. The initial tensile and compressive moduli may even be different in some cases, and hence the material would be called bimodular. Even though composites may be bimodular, the initial moduli are often close to the same value. In such cases, the non-linear behavior can be neglected for small strains.

1.2.3 Environmental Effects

Like other materials, composites expand and contract with temperature changes. However, because of their anisotropy, composites expand differently in the 1-direction than they do in the 2- and 3-directions [6]. Generally, fibrous composites have higher coefficients of thermal expansion transverse to the fibers (α_2) than they do parallel to the fibers (α_1). In fact, some carbon fiber composites have a negative value for α_1. In addition, composites also expand with increased moisture absorption. Expansion due to moisture absorption is also more pronounced transverse to the fibers than parallel to them [7].

Besides thermal and moisture expansion, environmental exposure can have a profound impact on the mechanical properties of advanced composites. High temperatures and/or continued exposure to moisture or radiation can significantly alter the mechanical properties of composite structures such as those in aerospace vehicles. Research is currently under way to understand these problems and develop ways to minimize the adverse effects [8-10].

1.2.4 Interlaminar Stresses

Because of the mismatch of the elastic constants in each ply of a laminated composite, internal stresses can result in the composite. As a consequence, shear and normal stresses must balance out these forces on the edges of the laminate. These stresses are confined to a region very close to the free edges and are known as the free-edge stresses. Figure 4 shows a detail of a laminate in which very complex loading is generated by simply subjecting it to a uniaxial load in the x-direction [2].

Stresses in laminates can also result from mismatches in thermal coefficients of expansion in the 1- and 2-directions (α_1 and α_2). These are called curing stresses, since they are generated when the composite cools down from the cure temperature. In some cases, these curing stresses can be large enough to cause matrix failure even when the external applied load is zero [3]. Therefore, it is important to know what parameters affect these inter-laminar stresses and how they can be controlled.

1.2.5 Scaling

The design of full scale structures is usually based on data from small specimens. Therefore, it is important to know whether the mechanical properties of composites depend on size. The effect of scaling on the mechanical properties may become significant, in which case it would be necessary to use some sort of scaling factor or theory to extrapolate the results to full scale structures or components [3, 11, 12].

1.2.6 Flaws

Because composite materials tend to be brittle, they are very sensitive to fabrication-induced flaws. These flaws may be imperfections in the fibers, fuzzballs included in the prepreg, or they may result from foreign particles included during the laying-up process. In any case, composites are fabrication-sensitive. When a flaw is included in a laminate, stress concentrations are caused and the structure is weakened. Moreover, different batches of material usually vary somewhat in their material properties.

Variations in fabrication technique may contribute further to mechanical property degradation. For example, small differences in lamination angle can have a distinct effect on the properties of the laminated structure. Flaws are, however, part of the reality of working with composite materials, and therefore the design of any structure must take into account this statistical variation in the mechanical strength.

1.2.7 Statistical Considerations

Because of the expected variability in material quality, strict guidelines are needed in the analysis and presentation of test data. Without such guidelines, composite materials cannot be used with confidence in primary structures. MIL HDBK 17 [13] contains a practical set of information concerning the statistical analysis of data. Included are procedures for calculating one-sided tolerances such as the B-basis values for data that fits a normal distribution. A value reported as a B-basis value indicates that 95% of the samples will meet or exceed the stated value with a 95% confidence level. An A-basis value indicates that 99% of the samples will meet or exceed the stated value with a confidence level of 95%. See references [14, 21] for calculation of A-Basis values. For the design of secondary structures, typically the B-basis values are used. For the design of primary structures, A-basis values must be used. In order to obtain a good B-basis value, one needs at least 20 specimens. For a good A-basis value, the number should be 35 to 40. A- and B-basis values can be calculated for fewer samples, but the A-basis or B-basis value calculated drops sharply from the mean value for fewer specimens. MIL HDBK 17 outlines other one-sided tolerance limit factors for use with Weibull and other distributions [13]. The more specimens tested, the closer the one-sided tolerance values will be to the mean property measured while still maintaining a 95% confidence level. ASTM and other standard test methods typically recommend testing only 5 coupons. Data obtained from so few tests will result in significantly low one-sided tolerance values.

Table 1 shows a group of 15 randomly ordered data points with typical scatter for composite materials. The values shown are ultimate strengths for unidirectional tensile tests (in ksi). The mean strength and standard deviation were obtained from reference [15]. If only 5 points are selected as per the standard test methods, the results vary significantly depending on which 5 are chosen. For instance, the mean for group (c) is 6.7% lower than the mean for all 15 specimens. Means for groups (b) and (c) differ by 10.7%. Only by evaluating a large number of data points can a reliable value be obtained. If the data were to be used for, say, an airframe, it is critical that the data be accurate since over-design results in undesirable weight penalties.

1.3. STANDARDIZATION

For the efficient, safe and wider use of composite materials in engineering structures, standard methods of testing and data reduction must exist. This has led to a vast effort to define, develop and use standard tests that will effectively characterize composite materials. Many test methods now exist for mechanical characterization of high strength and modulus materials; but there is little consensus as to which test is best for a given property and material. ASTM and other groups have published standard or recommended tests, but these may be inadequate or misleading. Some tests yield only "apparent" values for stiffness or strength, not actual values. In general, each member of the composites industry may use its own in-house tests or techniques for the characterization of composite materials. Material suppliers, structures manufacturers, government labs, and academia may all use different material property tests, depending on their goals and objectives. Therefore, standard guidelines must be established so that each individual or group can compare data obtained independently.

Another complication is the fact that different stages of the composite manufacturing process need material property data, but needs may vary from one application to another. A test used to obtain a value for quality control during, say, a prepreg manufacturing process will obviously not require the precision of a test used for design allowables. Lockett [16] outlined three distinct processes for which material property information must be obtained.

- preliminary material selection
- product design
- processing and fabrication

Preliminary material selection could further be divided into material screening and material qualification or certification. Each of these areas requires different types of tests. The establishment of firm standards for the material selection and product design areas has been a primary objective of MIL HDBK 17 [13] for some years now.

For preliminary material selection, there is a need for a database of mechanical properties for a wide selection of materials; and this information needs to be readily available. Once the material is selected and certified by the appropriate government agencies for use in industry, different and more detailed information may be needed in order to develop design allowables. Finally, after the part is designed, the component or subcomponent must be tested before it can be readied for production. Although there is no way to standardize component or subcomponent testing, standardization of material selection tests and design allowable tests, both for test procedure and data reduction, is the only way that material suppliers, users and researchers can effectively communicate to meet the demands of manufacturing composite structures. This being recognized, the special nature of composites must be taken into account in developing new standards for stiff, strong, anisotropic materials. Some progress has been made, but much more work needs to be done.

1.4. RECOMMENDED AND STANDARD TEST METHODS

There are several organizations that have worked to standardize procedures for testing of composite materials. Their objectives have been to reduce the amount of variability in material property data testing. As stated before, a certain amount of variation of properties is expected in a given material due to differences in batch properties, flaws, etc. In addition to these, variations may be introduced by the test set-up or specimen design. The purpose of standard test methods is to limit the variation due to differences in method. In this manner, variations in results obtained by independent studies of the same property for the same material will be minimized.

Several test methods which are currently defined are listed in tables 2, 3 and 4. ASTM and SACMA tests are used mainly in the United States. Of these two, ASTM is the organization that defines standard test methods to be used for material property evaluation. In addition, SACMA has defined what it calls recommended test methods. While not carrying the full weight of a standard test method, these are tests that SACMA feels best represent the materials suppliers needs. Many of SACMA's recommended test methods are based on ASTM tests. CRAG tests are recommended test methods used mainly in Europe.

Although many of these test methods are similar, results obtained from similar tests under the different standard or recommended definitions can be significantly different. For instance, the simple uniaxial tensile test as defined by CRAG gives stiffness and strength results that are about 6% and 8% higher, respectively, than results obtained by its ASTM counterpart [20]. Other more complicated tests can yield much higher variation between methods. Therefore, one test must be settled upon for each given property and/or material system, with appropriate guidelines established for their use. For composites, it is possible that no ideal test may exist at all. In this case, for comparison purposes, the test that is considered the best of the alternatives must be chosen.

Any standard test method must meet certain criteria. Following is a partial list of criteria that should be met by such a test method.

- Well defined, simple and cost-effective procedure
- Simple data reduction
- Test fixture simple and cost-effective
- Specimens small, economical, easy to fabricate and handle
- Accurate and repeatable measurements of intended property
- Mode and region of failure repeatable
- Capable of being tested on standard testing machine
- Environmental testing capabilities
- Complete documentation required
- Validity checked by analysis

The test must be well defined both in the test procedure and in the data reduction if similar results are to be reproduced independently. Without narrow definition, there would be too much possible variation in such parameters as specimen dimensions, rate of strain, etc. However, because it is necessary to have a certain amount of flexibility within the test method, the test procedure must require complete documentation. The data obtained from the test must be accurate, and the test must be representative of the end result for which the property is being measured. In addition, the specimen must be designed to suit the complex nature of composite materials.

Besides current recommendations and standards defined by ASTM, SACMA and CRAG, there are many test methods that material suppliers and manufacturers have devised for their own use. In some cases, these tests may not be accurate or representative of a given condition. Although there is growing consensus among the different members of the composites community as to which tests are best for a given application, there is still a significant amount of debate in certain areas. The needs of a given organization will vary depending on whether the group is a material supplier, material user, government laboratory, or academic institution. Many members of these groups have developed their own in-house tests, and some of these are of potential value to the composites community as a whole. Those considered potentially useful for general application have been submitted to ASTM for consideration to become standard test methods. Table 5 shows some tests that are under consideration for standardization.

1.5. PROJECT GOALS

With the accelerated use of advanced composite materials in structural applications, there is an increasing need for reliable, easily accessible composite material property data. Although material suppliers offer material property data for their products, the designer may find that more detailed information is needed in order to make specific decisions regarding which material system to use, or how to design a structure. Responding to the needs of industry, government agencies, and academia, CCMS has undertaken the task of developing a comprehensive material property database which will contain reliable material property data selected according to predefined guidelines. Moreover, the database will include a list of commonly used test methods together with background information on the limitations and advantages of each method. The purpose of this project was to develop the appropriate guidelines for screening composite material property data to be entered into this database. An integral part of this assignment was the selection of the material properties of interest and test methods to be used.

Because of the number of composite material systems available, only a few basic properties were selected for initial entry into the database. In the future, further material property data will be included. The properties selected for this initial phase of the project were:

1. Uniaxial tension
2. Uniaxial compression
3. In-plane Shear

The test methods selected were chosen from standard or well established tests that have been adequately documented and researched. In order to select a test for a given property, literature pertaining to each of several candidate tests was reviewed, and consultations were conducted with experts in industry and academia. It is felt that the methods chosen satisfy as well as possible the criteria for a good test method. Special attention was given to accuracy and simplicity of the test.

CHAPTER 2. TENSION

The uniaxial tensile test is perhaps the most agreed upon test available for the determination of composite material properties. This is due to the fact that in comparison with compression and shear, it is relatively easy to achieve and maintain a state of pure and uniform tensile stress until failure. However, regardless of its apparent simplicity, there are several aspects of the tensile test that can affect the accuracy of the results obtained.

The objective of the test is to obtain valid failures, which are failures that occur in the gage section away from the grips. Because composites are very strong and stiff, and because they are also brittle, alignment in the grips of the testing machine is critical. Slight misalignment can cause premature or invalid failures of the specimens.

Although misalignment will be a factor in any tensile test, the nature of the test itself can introduce errors in the results obtained. Therefore, the design of the coupon and method of gripping must reflect the special nature of composite materials, or the resulting data will not be accurate.

2.1. TEST METHODS AVAILABLE

Because of the simple nature of the uniaxial tensile test, there are relatively few tensile test methods available for composite materials. Table 6 lists the applicable standards for tensile tests under ASTM, SACMA and CRAG definitions. The tensile tests specified by these three organizations are all similar, but there are some important differences.

2.1.1 ASTM D 638

This test was originally developed for the testing of homogeneous, isotropic materials such as metals and plastics. See Figure 5. The dogbone coupon is loaded using wedge action or hydraulic grips on the tab sections. The reduced section is designed to initiate failure away from the grips. Little success has been found by those who have tried to adapt this test to composite materials. Because of the waists that have to be machined into the sides of the specimen, and because of stress concentrations, the edges tend to delaminate and cause early failure. The dogbone test can be used for neat resins, but is not recommended for laminated composites.

2.1.2 ASTM D 3039 and SACMA SRM 4

Figure 6 shows the basic geometry of the ASTM or SACMA coupon. The coupon has straight parallel sides, and is recommended for both unidirectional specimens and symmetric orthotropic laminates. The glass/epoxy end tabs are bonded to the specimen. For testing, the specimen is gripped in the tab section by either wedge action or hydraulic grips. This test is the one that is largely accepted by the U.S. composites community as the standard tensile test for design allowables.

One of the key features of this coupon is the end tab region. The ASTM and SACMA specifications suggest the use of a non-woven glass and epoxy crossply laminate for these tabs. The tabs are said to be necessary for the grips to have sufficient hold on the laminate and to protect the specimen from damage by the grips. The taper reduces stress concentrations from clamping as much as possible. However, a significant number of coupon failures occur in the grip area, and from time to time the end tabs shear off before the specimen fails [21]. End tab shearing is eliminated by lengthening the tabs. This ensures that the shear stresses are reduced to the point where the specimen will fail in tension in the gage section before the ultimate shear stress in the tab adhesive is reached. Nevertheless, it is apparent that tensile failure in the grip area is an unavoidable part of the test.

2.1.3 CRAG 3.1 and 3.2

Figure 7a shows the CRAG 3.1 unidirectional coupon and Figure 7b shows the CRAG 3.2 multidirectional coupon. Again the tabs are bonded on and gripped by a standard testing machine for failure. Although the CRAG specimens are similar to the ASTM coupons, there exist some important differences. First, CRAG suggests the use of aluminium end tabs instead of the glass/epoxy suggested by ASTM. Also, there is no taper machined into the end tabs. This makes the tabs cheaper and easier to machine. However for the unidirectional specimens, half of the thickness of the specimen is machined away. Although this eliminates the problem of having end tab failures, it complicates the fabrication procedure somewhat. In addition, flaws introduced by the machining process may alter the apparent properties of the material.

2.2. DISCUSSION

Although SACMA SRM 4 is based on ASTM D 3039, the ASTM test is more general. Whereas ASTM defines the tensile modulus as $\Delta\sigma/\Delta\varepsilon$ anywhere along the stress/strain curve, SACMA restricts the calculated tensile modulus to a specific value. This is the slope of a line passing through the stress/strain curve at two specified levels of strain. See Figure 9. The choice of the two points is somewhat arbitrary and may be misleading . Depending on the material system being tested, the shape of the stress/strain response curve will vary. However, according to SACMA specifications, the same two strains will be used for calculation of the modulus. If different points were used, a different stiffness would result.

In order to facilitate the testing of tensile specimens, there have been methods found that do not require the extra steps of end tab bonding and machining. One method that has worked quite well is to wrap a strip of medium grit emery cloth (Figure 8) around the ends of the coupon (grit facing in) before it is inserted into the jaws. This lends enough friction to hold tensile specimens with or without hydraulic grips, and protects the specimen from coarse serrations in the jaws [22]. Another similar method is to use some soft plastic instead of emery cloth. For example, a strip of polyethylene could be wrapped around the coupon ends (Figure 8). These methods have the advantages that they are extremely easy (no machining of bonding of the end tabs), and they are generally more effective than glass/ epoxy tabs, although occasional grip failures still occur.

End tabs were necessary in the early days of composites research when testing machines were designed to pull metal specimens. Because they are coarsely serrated, the jaws used for metals are not appropriate for pulling composite specimens. However, jaw design today has been improved to the point where for many layup configurations, there is no need for end tabs [23]. The standards have not been changed to reflect this.

Even with coarsely serrated jaws, the necessity of end tabs is a somewhat stacking sequence-dependent requirement. End tabs are really only needed if there are 0° plies on the outer surface of the specimen where they can be damaged and hence reduce the tensile properties. If, say, ±45° layers are on the outside of the specimen, these compliant layers can absorb some fiber damage without affecting the overall tensile properties.

As mentioned before, the ASTM D 3039 and SACMA SRM 4 tensile tests will yield a significant percentage of grip failures. Given this fact, two questions come to mind. The first question is whether or not, when reporting the data, these end tab failures should be included in the determination of the mean value. The second question is whether the waists machined into the CRAG 3.1 specimens could constitute a valid solution to the end tab failure problem in unidirectional specimens.

To address these questions, it is helpful to understand the nature of the composite and what affects the strength of the specimen. Because composites are relatively brittle, they are very flaw-sensitive. In practice, there are many types of imperfections that can be incorporated in a composite laminate. Broken or damaged fibers may be included in the prepreg as well as fuzzballs or foreign particles. The layup process also introduces opportunity for extra flaws to be introduced. These imperfections generally cause early failure because of the stress concentrations they cause.

Figure 10 shows a schematic of the ASTM D 3039 coupon with various flaws represented within the laminate, along with representations of the maximum tensile stresses along the length of the specimen. Clearly the measured tensile strength will very much depend upon the distribution, nature, density and exact location of these flaws. A flaw contained in the end tab region may have no effect on the apparent tensile strength of the coupon, since most of the tabbed region experiences low tensile stresses as the load is transferred by shear from the end tabs. In this case (Figure 10a), the coupon is expected to fail in the grips due to the stress concentrations introduced by clamping. The applied stress should be near the ultimate strength of the material, although if there were no stress concentration introduced by the end tab and no flaws located in the gage section, the coupon would fail at a still higher applied stress. In practice, the only way a gage section failure occurs is when a flaw is located in the gage section, making it the weakest link in the structure. In this case (Figure 10b), the applied stress at failure is expected to be lower than the ultimate strength of the material, and lower than that of the specimen shown in Figure 10a. The third possibility is shown in Figure 10c. Here, a flaw may be located in the area of the coupon that already experiences stress concentrations from clamping. Failure is expected to occur in the grips at a low applied stress due to the compounded effect of the clamping and flaw stress concentrations.

When a flaw exists in a laminate, the probability of the flaw being contained in any of the three regions discussed above is proportional to the percentage of the coupon area occupied by the region. Hence, the most likely area for a flaw to be contained is in the gage section, since it represents most of the area of the coupon. The next most likely place for a flaw to be located is inside the tabbed region away from the tapered tips, where the tensile stresses are low. The least likely location for a flaw is in the region of the end tabs that experiences stress concentrations due to clamping. Therefore, most failures will occur in the gage section. However a significant percentage of failures will occur in the tabbed regions, most of which will occur at an equal or higher stress than the gage section failures. This phenomenon of grip failures occurring at equal or higher stresses than gage section failures has been noted amongst other by [21]. For this reason, it is felt that the end tab failures that occur at a higher stress than the average gage section failure should be included when reporting mean property data. Those grip failures that occur at lower stresses are probably due to combined stress concentrations.

Sottos *et al.* [20] compared ASTM standard tests with CRAG standards and noticed that the CRAG unidirectional tensile test gives 6% higher strengths than the ASTM test. Only five specimens were tested for each test method, so it can not be said that their findings are statistically meaningful, but this same argument of flaw location suggests that the CRAG test would indeed give higher strength results. Figure 11 shows the unidirectional CRAG coupon with various flaws represented within the laminate.

Regardless of the location of the flaw, failure is confined to the gage section since the specimen is only half as thick there. Given this, and the fact that statistically it is more probable that a flaw will be located outside the gage section, as in Figure 11a, the coupons will usually fail at a higher applied stress because there are usually no flaws contained in the gage section. Occasionally, a flaw will be located in the gage section, as in Figure 11b and failure will occur at a lower applied stress. But on average, the CRAG coupons will exhibit a higher ultimate strength than the ASTM or SACMA tensile test. In effect, this is a scaling phenomenon. The larger the gage section, the more likely it is that a weakening flaw will be included, and hence the lower the apparent strength will be.

In addition to the above, there are problems to be expected any time one machines away half of the specimen thickness. As indication that the data obtained from CRAG tests may be affected, Sottos *et al.* [20] noticed not only higher strength, but higher modulus in CRAG specimens as compared with ASTM samples.

CHAPTER 3. COMPRESSION

The uniaxial compressive test is one of great importance for several reasons. Unlike metals, cracks can propagate under compressive load in composites. Also, the strain hardening behavior that composites exhibit in tension can be reversed in compression, making the response in compression typically strain softening. Therefore, compressive data are valuable since the response of compression members often becomes a dominant factor when composites are subject to cyclic loading and/or environmental exposure [24].

However, composites possess unique properties that make compressive testing very difficult. Because of their high stiffness and strength in the direction of the fibers, and their sensitivity to flaws and eccentric loading, consistent compressive data are difficult to obtain. In fact, there are those who argue that one cannot identify a compressive material property, only a compressive structural response which depends on factors such as loading method, specimen geometry, etc [25, 26]. This is because compressive behavior is more matrix-dominated than tensile behavior is. This dependence on matrix properties results in compressive data that may vary widely with different batches of the same material, or with different test setups.

Although little can be done to decrease batch-to-batch variation, a test method that reduces the amount of variability due to other factors has been sought for some time now. Even if a true compressive property is not possible to measure, some form of compressive information is needed for comparison with other materials.

There are two main ways to transfer load to the test specimen. Specimens can either be end loaded or shear loaded (usually through end tabs), or can be loaded by a combination of end loading and shear loading. See Figure 12. Because of Poisson effects and geometric non-uniformities in the specimen ends, end loaded specimens tend to broom and crush at the ends causing premature failure. This effect can be moderated through the use of end tabs and/or constraining mechanisms, and by grinding the ends of the specimen flat and square. Brooming of the specimen is not a problem when the specimen is loaded through shear [27]. In this manner, the load transfer is much smoother, being distributed over a larger area instead of being taken by only a few fibers as it usually is in the case of end loading. However, shear loading does not work well for thick laminates because the compressive stress is non-uniform through the thickness, with the fibers at the midplane of the specimen being less stressed than the outer fibers. With a short gage section, these stress gradients cannot distribute themselves out to yield uniform compressive stress.

Compressive tests are also very sensitive to geometric eccentricities and alignment of the specimens with respect to the applied load. If the specimen is loaded eccentrically during compression, global buckling of the specimen can result. Figure 13 represents the stress/ strain response of front and back strain gages readings on a buckled compression specimen. Note that even before buckling occurs, eccentricities or load misalignment can cause out-of-plane bending in the axial compression specimen. This causes bending stresses to occur in the specimen, and the combination of these bending stresses and the axial stress applied to the specimen will cause failure at a mean compressive stress below the actual ultimate strength of the material. This is especially true of thicker laminates in the range of 0.254 cm (0.1 in) [28]. In certain cases, when the load is laterally displaced with respect to the coupon (Figure 14), these prebuckling bending stresses cannot be detected even with back-to-back strain gages located at the midspan of the gage section. This is because the bending moment, and hence the resulting stress, crosses zero at the midspan (see Figure 15). Back-to-back gages would need to be located at some other location, such as the quarterspan, in order to detect these bending stresses. Figure 14 shows two types of load eccentricities, both lateral and cantilever displacement. Figure 15 shows the resulting stress variations from the mean compressive stress σ_0 associated with the load eccentricities shown in Figure 14 [28].

Even when the specimen is aligned properly, buckling may still be a problem. There are three methods of avoiding global buckling. The first method is to use a relatively short gage length, such as in the case of ASTM D 3410 Celanese or IITRI fixtures. The second method for avoiding buckling is through the use of side supports, as in ASTM D 695 or variations. This type of test is very widespread in the composites industry because of its simplicity. Finally, the specimen can be constrained from buckling by using a sandwich-type structure. Such a specimen can be loaded in either bending or direct compression. The core material of the sandwich supports the specimen from out-of-plane displacement while hopefully not influencing other displacements. Each of these three methods has its advantages and disadvantages, including cost of material and fabrication, and suitability for environmental testing.

Compressive testing is further complicated by the fact that failure is somewhat a matter of definition, rather than being clear cut. True compressive failure of the fibers is difficult, if not impossible to obtain. Usually some other mode is observed which is more typical of a structural instability, rather than a material response. Some of the more common modes of failure noted by Schoeppner and Sierakowski [29] are:

- end brooming
- matrix cracking between adjacent fibers
- global buckling
- shear fracture
- local fiber buckling

Some of these failure modes may be valid and some not. Different fixtures, and even different materials in the same fixture will produce different failure modes. When analyzing compressive property data, one must decide which modes constitute valid failures. This is an additional variable in the test data, and therefore when reporting compressive data, the failure mode must be included. No ideal solution yet exists for compressive testing. The best solution will have to be a compromise of the best alternatives. Some shortcomings will have to be expected and should be understood as such.

3.1. TEST METHODS AVAILABLE

There are many compressive tests available. The need for accurate compressive data has motivated many researchers to look for adequate test methods. In 1987, according to Adsit's recommendations, ASTM accepted two new test methods as standard [27]. These were the IITRI compression test and the sandwich beam test. Tables 7, 8 and 9 list the ASTM, SACMA and CRAG compressive test methods respectively.

In addition to the tests listed, there are a number of other compressive tests which were either developed independently or modified from one of the standards. Reference [29] gives a brief introduction to some of these test methods. These tests are used by different institutions in industry, education and government, and most of them can be grouped into the following major categories [24, 29]:

- unsupported compression coupon
- supported compression coupon
- sandwich beams and columns

In addition, any of these specimens can either have a reduced section or could be straight-sided, and the method of loading for any of these tests can be through either shear or end loading.

3.1.1 Unsupported Compression Coupons

In order to avoid global buckling of the specimen, the unsupported specimen must have a short, relatively thick gage section. Both shear and end loaded test methods exist, but by far the more common technique is shear loading. Typical tests of this type are performed with the Celanese and IITRI fixtures and specimens shown in Figures 16 and 17. Both of these tests employ wedge action grips that hold the specimen in place during the loading process. The grips are held in alignment by some means of constraint. The Celanese uses an outer sleeve that aligns the grips. The IITRI test fixture has linear bearings to keep the grips aligned.

Unsupported specimens have the distinct advantage that the gage section is free from any external constraints that could impart friction or otherwise distort the compression data. However, some significant disadvantages exist also.

3.1.2 Supported Compression Coupons

In this type of test, global specimen buckling is prevented by the use of some sort of lateral support to the specimen gage section. The purpose of the lateral support is to prevent any out-of-plane displacement of the coupon. As a general rule, these specimens are end loaded, although some shear loaded fixtures exist. Figure 18 shows two typical face supported fixtures.

The SACMA SRM 1 (see Figure 18b) test uses two specimens to measure compressive properties. The modulus specimen is an untabbed, straight-sided coupon. It is not loaded to failure. The strength specimen is tabbed, much like specimens used in the Celanese and IITRI fixtures, except that the gage length is much shorter. However, the fabrication of these tabbed specimens is easier since it is not as critical that the faces be flat and parallel. Two fixtures are required also. The faceplate for the modulus specimen has the grooves machined away to accommodate strain gages. See Figure 18b.

The procedure for testing supported specimens is much easier than that for the unsupported specimen tests. Because the face supports lend stability against buckling, alignment in the testing machine is less critical. Because of this, the fixtures are less bulky and are easier to work with. However, the effect of the support upon the compressive response of the specimen is not well understood.

3.1.3 Sandwich Beams and Columns

In recent years, the sandwich beam has gained some acceptance in the composites industry. It was recently accepted as an ASTM standard compressive test according to Adsit's recommendations [27]. The beam is loaded in four-point bending so that the entire test section is loaded in pure bending. Since the top, or active face is relatively thin, the loading is assumed to be uniformly compressive. The active face is made of a thinner laminate than the bottom so compressive failure is assured. Figure 19 shows the basic setup for the test.

In principle, this specimen reduces the buckling problems associated with having an unsupported gage section. It also solves some of the problems of the face supported systems because there is no binding or additional friction with the support in the beam (the core material is assumed to have negligible effect on the compressive properties of the laminate).

The test is relatively simple to perform, and the stress concentrations should be minimal for this type of specimen.

Lagace and Vizzini [30] state that because of the curvature induced in the four-point bending test, potentially valid failure modes such as ply buckling and delamination might be prevented. In order to eliminate this problem, Lagace and Vizzini proposed the use of a sandwich column, shown in Figure 20. The face sheets for the column are of equal thickness, and the specimen is loaded directly in the grips of a standard testing machine.

3.2. DISCUSSION

By far, the most popular unsupported coupon tests are the Celanese and IITRI tests [31]. There are other unsupported gage section tests [29], but Celanese and IITRI are the tests that have gained acceptance in the composites industry. Although they are very commonly used to produce compressive data, some disadvantages exist for each of these tests.

First, to avoid stresses caused by out-of-plane bending, it is necessary to ensure that the alignment is extremely precise. In order to accomplish this, machining of the specimen must be very accurate with care being taken to keep the end tabs flat and parallel [24], and symmetric about the specimen. Also the precise alignment requires a fixture that is expensive and cumbersome.

A second drawback of the Celanese and IITRI tests is the fact that the gage section is so short. Because St. Venant's principle may not be satisfied, it has been questioned by some whether the stress field is uniform in the gage section [24, 32]. Clamping forces may not have a chance to become distributed through the thickness in the test section to yield uniform compression. This is especially true for thicker laminates where shear loading causes the outer fibers to be initially stressed more than the inner fibers. Reiss *et al.* [32] used a modified Ritz approach together with classical lamination theory to study the constrained edge effect for compressive testing with perfect gripping and alignment. They reported that for unidirectional specimens, the biaxial state of stress due to clamping constraints was confined to small regions in the corners of the gage section. However, for general laminates this is not the case. In any case, there exist stress concentrations at the end tabs that affect the ultimate strength measured in this way.

Berg and Adams [33] and Sinclair and Chamis [34] reported that unidirectional graphite/ epoxy samples failed in the end tab region. This may be due to the stress concentrations directly, or, as some have suggested, it may be that the end tabs begin to partially debond. This would essentially lengthen the unsupported gage length, and hence precipitate out-of-plane effects which cause premature failure in the grips [28].

Lastly, these fixtures do not lend themselves well to environmental testing. Any bulky fixture will require large thermal soak times due to their thermal mass.

The next most common compressive tests are ASTM D 695 and the modified ASTM D 695 or SACMA SRM 1 [31]. Specimens of this type were designed to eliminate the problem of having a non-uniform stress distribution due to short gage section and shear loading. The thermal mass of the fixture is also greatly reduced, so environmental testing is facilitated. Finally, the test fixture is far less expensive and is easier to handle, and the coupon is simple to fabricate (even if end tabs are used, since flatness and parallelism are much less critical).

This type of test has some disadvantages however. First, two specimens must be used in order to get both a strength and modulus value. This means that the whole stress/strain curve cannot be found with this method, since the strength coupon's gage section is too short to accept a strain gage. If one tries to load an untabbed specimen to failure in order to produce the entire stress/strain curve, it has been reported that the specimen shows signs of buckling despite the use of lateral supports [24]. The out-of-plane bending may not immediately lead to catastrophic failure, but probably leads to premature failure. This may not be surprising due to the large gage length. Second, because lateral pressure varies with bolt tightness, the friction added by the face plates tends to be of an uncontrolled nature. Hence modulus readings will be affected . Berg and Adams [33] reported that they obtained higher moduli and lower strengths with face supported specimens than with unsupported specimens . They attributed the modulus differences to friction, and the strength differences to specimen end loading. It has also been reported that the face supports may restrict some valid compressive failure modes [30].

Adsit showed that ASTM D 695 is simply not a reliable method for composites [27]. Therefore it will not be discussed further in this report, but modified ASTM D 695 tests are used extensively in industry and will be discussed.

The sandwich beam test is not a good candidate for basic property evaluation because of the size of the specimen. While a typical IITRI or SACMA SRM 1 specimen is about 0.5 in by 10 in (Celanese specimens are narrower), the sandwich beam specimen is about 1 in by 20 in. In addition, there are two faces for each specimen, and the bottom face is twice as thick as the top. This means that the sandwich beam uses at least 10 times as much composite material per specimen, as well as using the honeycomb core material. Fabrication is also time consuming, expensive and difficult to do correctly. Due to the constraint imposed by the core material, this specimen cannot be used to find Poisson's ratio in compression. One of the major drawbacks of the test is that parts of the composite skins may not bond well to the core material, causing problems with local buckling and premature failure [30].

The sandwich column specimen still has all of the disadvantages of the sandwich beam except that it may allow a wider range of compressive failure modes to occur. It will not be discussed further.

There are other tests methods including those with unsupported and supported gage sections, but they have gained far less acceptance in the composites industry. Therefore, the test methods that will be considered in the conclusions are the ASTM D 3410 tests, the modified ASTM D 695 tests such as SACMA SRM 1, and the sandwich beam. Of these, the modified ASTM D 695 tests are probably the easiest to perform, whereas many researchers regard the IITRI test to be the most accurate [35, 24].

CHAPTER 4. SHEAR

Test methods for the in-plane ply shear properties are much more diverse than those for either tension or compression properties. Test methods for shear response can have test procedures and specimen geometries that range from the simple to the very complex. Most methods are not adequate for accurately describing the stress/strain response, not only because of the unique nature of composites, but because of the special requirements needed for shear response characterization. While it is relatively simple to achieve a pure state of tension or compression, it is difficult to impart a pure and uniform state of shear on any significant portion of a test specimen. Some tests impart uniform shear over some area of the test section, but suffer from stress concentrations. Others have the largest stresses in the gage section, but the stress is not pure shear. One method that is thought to achieve pure and uniform shear stress over the whole test specimen is the thin-walled tube loaded in torsion. Because the state of shear stress along known axes is ensured, many researchers have used the torsion tube as the standard against which other tests are judged. However, this test proves to be prohibitively expensive for standard material characterization because of the nature of the specimen and the equipment needed to run the test.

4.1. TEST METHODS AVAILABLE

ASTM, SACMA and CRAG define a total of three test methods for shear properties. Of these, two are used for in-plane properties. The other, the short beam test, is recommended only to determine apparent interlaminar shear strength. Tables 10, 11 and 12 show the available test methods, while Table 13 gives a list of some of the more common non-standard tests. In Table 13, only test methods that allow the measurement of both strength and stress/strain response were listed.

Each of the tests in Table 13 has been proposed for in-plane shear characterization of composite materials. The objective of any standard test is to adequately characterize the material, and do so simply and inexpensively. Some of these tests come near this goal, but many fall short for one reason or another.

4.1.1 ±45° Tensile

Figure 21 shows the ASTM D 3518 coupon. This test is simply the standard ASTM D 3039 tensile test using a ±45° laminate. Both SACMA SRM 7 and CRAG 5.1 also define the ±45° test as a recommended test method. Although ASTM specifies no specific stacking sequence, laminates are restricted to balanced symmetric layups, and have thickness restrictions. SACMA recommends a $[\pm 45^\circ]_{2S}$ laminate, and CRAG recommends a $[\pm 45^\circ]_{ns}$ laminate for property testing. Although end tabs are specified by all three standards, this specimen needs no end tabs [21]. Using orthogonal transformations and laminated plate theory, the in-plane (ply) shear response can be calculated from the uniaxial tensile response of the laminate. The laminate has to be symmetric and have no shear/ extension coupling [36]. Woven materials are not recommended for use with this test.

Being a uniaxial tensile test, this is an extremely easy and cheap test to perform, and the specimen is easy to fabricate and handle. However, if the entire stress-strain response is desired, an extensometer may be required, since typically the strains to failure are quite high and strain gages tend to be damaged before final failure occurs.

4.1.2 Short Beam Shear

ASTM D 2344, SACMA SRM 8 and CRAG 2.1 (see Figure 22) all define the short beam shear test for apparent interlaminar shear strength. Because of its simplicity, some have used this test to measure the in-plane shear strength by assuming that the in-plane shear strength is the same as the interlaminar shear strength for a unidirectional laminate. The specimen has to be relatively thick compared to its length in order for shear failure to prevail. No modulus properties are obtained from this test. The test has been widely used for quality control purposes in manufacturing applications.

Stinchcomb *et al.* [37] found that the failure of good quality short beam shear specimens is always a mixed-mode microbuckling/shear failure and not a pure interlaminar shear failure. Pure shear failure only occurs in poor quality specimens. Chiao and Moore [38] found that for this test, the results often could not be reproduced even for specimens made by the same process and tested by the same person. However, the test is very simple to perform, uses very little material (the specimen is about 0.75 in by 0.375 in by about 0.125 in thick), and can afford a qualitative evaluation of the material.

4.1.3 Torsion tube

The torsion tube specimen is shown in Figure 23. From an applied mechanics point of view, the torsion tube is the best test method for shear stress/strain characterization. If the test is carried out in an ideal manner, the entire test section experiences pure and uniform shear stress τ_{12}. The tube wall must be thin, so that the stress variation through the thickness is negligible.

The tabbed specimen is mounted in the grips of a torsion testing machine and either the angle of twist or the strain at ±45° planes is measured for calculation of shear strain. Care must be taken to ensure that only pure torsion is applied. No axial, transverse shear or bending loads can be applied.

In order to average out the effects of possible non-uniformities in the specimen thickness, several strain gages are required at different locations around the tube. In practice, due to the complexity of the specimen fabrication and test procedures, the torsion tube cannot become a standard test. One crucial disadvantage of this test is the fabrication of the specimen itself. It is a very difficult to accurately maintain a uniform wall thickness that will not buckle when loaded.

4.1.4 Torsion Rod or Bar

The specimen for the torsion rod test is shown in Figure 24. This test is very similar to the torsion tube, but the stress is, of course, not uniform throughout the specimen. This test has basically the same advantages and drawbacks as the torsion tube, except that it may be slightly less expensive to fabricate, and transverse and bending loads may not affect the results as much due to its small diameter. It can either be shaped in a mold or be pultruded. The diameter of the rod must be kept small.

4.1.5 Iosipescu

The Iosipescu double notched specimen was first proposed by Iosipescu for shear testing homogeneous materials [39]. It has since been studied by many investigators for use with composites [40-43]. An area of relatively pure and uniform shear should be generated in the gage section between the notches by applying opposing force couples. This should also be the area of greatest shear stress due to the reduced section. Theoretically, either the 0° or the 90° fiber orientation should give the same in-plane ply shear properties. There are several loading methods for this test, each having its own data reduction scheme. The Iosipescu specimen along with three loading techniques is shown in Figure 25.

The most common methods of loading the specimen are with the modified Wyoming fixture (WF2) [40] developed by the University of Wyoming (see Figure 25b), and with an antisymmetric four point bend fixture (AFPB) [41] (see Figure 25d). Abdallah [41] has reported that the AFPB test provides more uniform stress field and therefore should give more consistent results. In either case, the specimen is placed in the fixture and loaded using a standard testing machine. Both specimen fabrication and test procedure are relatively simple, although machining the notches represents some expense.

This test has been proposed as a standard test for shear properties. In fact, ASTM is now in the final stages of accepting it as such [44]. Compared to the ±45° specimen, the test is more expensive, not only because of the notches machined into the coupons, but the loading fixture represents a somewhat significant initial investment.

4.1.6 10° Off-Axis Tension

Like the ±45° test, the greatest appeal of this test is its simplicity. It is a simple tensile coupon, with the fibers at a 10° angle from the load axis (see Figure 26). Chamis and Sinclair [45] suggested the use of the 10° off-axis tensile test for shear properties. Like the ±45° test, orthogonal transformations are used to describe the shear stress/strain response of the ply from global tensile response. The data reduction assumes that the stress/strain characteristics are not affected by the biaxial stress state that exists in this specimen. The specimens are made from a 0° unidirectional laminate and cut at a 10° angle.

According to Chamis and Sinclair [45], the shear stress is uniform through the thickness. There are also no laminate residual stresses like there are in the ±45° test. Chamis pointed out that for carbon/epoxy with a fiber angle of 10°, the fracture shear stress is quite sensitive to small misalignments, and hence it is recommended that the fiber angle in the gage section be kept to within 1°. However, the fracture shear strain is relatively insensitive to misalignments, since the strain reaches a maximum near this angle [45]. 10° may not be the correct angle for other materials. Some suitable way of reducing the stress concentrations occurring from clamping a specimen with shear/extension coupling must be employed.

4.1.7 Rail Shear Tests

The two- and three-rail shear tests have seen widespread use in the aerospace industry, mostly as a structural response test. Because of popular demand, ASTM has published a recommended procedure for testing ply and crossply laminate properties , but it is not a standard test method [17]. Sims [46] introduced the three-rail shear test to avoid some of the problems with the unsymmetrical two-rail shear method. It is assumed that the gage section sees pure and uniform shear stresses. Both of these tests can use either bonded or bolted on rails. See Figure 27.

4.1.8 Cross Beam

The specimen for this test is of sandwich construction. In theory, the laminates used can be either $[0°/90°]_S$ or $[\pm45°]_S$. The legs are loaded in bending as shown in Figure 28, which creates a state of biaxial tension and compression in the test section. If the load is divided evenly between the four legs, the biaxial state of stress at the intersection of the arms will be equivalent to a pure shear load on an element at 45° to the legs.

4.1.9 Picture Frame

Since the specimen is rather large, the panel is made as a sandwich laminate for stability against buckling. The four bar frame (see Figure 29) is bonded or bolted on to the sandwich panel, and the assembly is loaded either on one or two axes. In order to reduce high stresses at the corners, they are usually cut off and doublers are bonded to the resulting free edges [47]. Laminates are usually $[0°/90°]_S$.

4.1.10 Panel Shear

The panel shear specimen is a thin plate with bonded end tabs as shown in Figure 30a. Figure 30b shows the fixture used to load the specimen. The specimen can be either unidirectional or crossply laminate. Terry [48] indicated that shear strengths of crossply laminates should be viewed cautiously since there is a certain amount of tensile loading of fibers that contributes to apparent strength. The specimen is bonded or bolted to the linkages of the test fixture, the load links are adjusted for the specimen and the panel is loaded in shear through the four bar linkage. The specimen and fixture both must be sized to avoid specimen buckling. In fact, in his research comparing shear test methods, Terry [48] had to support the face of his specimens with Teflon® coated blocks because the fixture he had available was too large for his samples. Avoiding this problem would necessitate the manufacture of a whole new test fixture.

4.1.11 Slotted Tensile

This specimen configuration has been suggested by Duggan *et al.* [49] . The test requires more than a standard standard testing machine, since loads are applied both axially and transverse to the specimen (see Figure 31). The test specimen consists of a standard tensile coupon modified by having two slots machined through the thickness parallel to the load axis. Tensile and compressive loads are introduced as per Figure 31, which induces a biaxial stress state equivalent to pure shear at a plane 45° from the load axis. The ratio of the loads P_1 and P_2 depends on the size of the rigid blocks and the distance between slots. Care must be taken that the ratio of loads P_1/P_2 is kept constant.

4.2. DISCUSSION

By far the most widely used in-plane shear test is the ±45° tensile test [31]. The only other two tests commonly used in the composites industry are the rail shear test and the Iosipescu test [31]. The Iosipescu is relatively new and has not gained broad acceptance. However, many researchers have studied this specimen and have found encouraging results.

Considering equilibrium it can be shown that the loading on the +45° or -45° planes is not pure shear (see Figure 21). Significant normal stresses exist. This is why the specimen is given a $[\pm 45°]_{ns}$ layup rather than simply a $[45°]_n$ layup. The fibers normal to the shear plane lend tensile strength so it is assured that the specimen will fail in shear. One of the problems associated with this test is that following large deformations, the fibers are no longer at 45° to the loading axis. Therefore, it is not completely understood how the ultimate shear strength should be interpreted since the direction of the final failure does not coincide with the plane of maximum shear stress.

Because of the lamination of the specimen, Rosen [50] stated that interlaminar stresses are probably a factor near the free edges. If present, interlaminar edge stresses would cause matrix cracking and hence premature failure of the specimen. Terry [48] stated that as long as the plies are stacked in as homogeneous an arrangement as possible, edge effects should be minimal. Terry [48] has presented results for $[\pm 45°]_{2s}$ and $[+45°_4/-45°_4]_s$ laminates which indicate a difference in the measured shear strength of 28.4%. The difference in shear stress was attributed to edge stresses and premature delamination in the blocked plies.

Similar results have been noted by Kellas and Morton [3]. In a scaling study, they showed that the shear strength measured can vary widely depending on the stacking sequence. SACMA specifications for the ±45° tensile test recommend $[\pm 45°]_{2s}$ as the layup, while

CRAG recommends a $[\pm 45°]_{ns}$ layup, and ASTM only restricts its specimens to balanced, symmetric layups.

Kellas and Morton [51] have noted, however, that the stress/strain response is dependent on the ply thickness. For instance, a $[\pm 45°]_{2s}$ laminate will have a different strength and strain to failure than a $[\pm 45°]_{8s}$ laminate. Ultimate strength can vary by as much as 30%, and strain to failure can differ by as much as 300% [3]. To illustrate why it is expected that this occurs, it is recalled from variational statistics that for brittle materials there is a correlation between the size of a specimen and its apparent strength. The larger the specimen, the greater chance there is that it will contain a critical flaw, and therefore, the weaker the specimen will appear to be on average. Figure 32 [51] shows two specimens. One is a $[+45°/-45°]_{2s}$ laminate and the other is a $[+45°/-45°]_{4s}$ laminate. In each case, the center ply consists of two -45° laminae. Being thicker, these center plies will have, on average, correspondingly lower shear strengths as stated already, and will fail first. The load will then be shared among the remaining plies. However, whereas in Figure 32b the weak ply constitutes only 12.5% of the total specimen thickness, in Figure 32a the weak ply constitutes a full quarter of the specimen thickness. Therefore, a specimen having the stacking sequence shown in Figure 32a will appear weaker than one with the stacking sequence in Figure 32b. In order to avoid such problems, which are associated with ply thickness, Kellas and Morton [51] have recommended that a $[\pm 45°]_{ns}$ laminate be used, where $n \geq 6$.

The initial portion of the shear stress/strain responses of $[\pm 45°]_{2s}$ and a $[\pm 45°]_{8s}$ laminates are quite similar, and the difference in strength and shear strain occurs only in the high strain region of the curve [51]. Because of this dependence of failure strain and strength on ply thickness, a standard stacking sequence should be specified, so that at least the results from different tests can be compared.

Some researchers have therefore proposed an offset strain criteria is to define shear strength and strain of the ±45° specimen. This procedure is not specified by any of the standards. Chiao *et al.* [52] defined a 0.2% strain offset as shear failure (see Figure 33). This procedure seemed to make their results agree well with those from the torsion tube, but it is doubtful if this offset criterion is a valid solution to the general case.

The main question that still remains about the Iosipescu test is that it is unclear how to interpret shear strength results. When the more popular 0° specimen is used, it is probable that an overestimate of the actual strength is obtained [43, 53]. When a 90° specimen is used, premature failure results [43, 54]. Thus the Iosipescu yields an upper and lower bound, but it is unclear what the actual shear strength is. Several researchers have pointed out that the specimen has significant stress concentrations at the notch tips [47, 53]. Therefore, there has been some research into the actual state of the stress field in the specimen.

Morton *et al.* [43] and Pindera *et al.* [54] found that the stress field is indeed not ideal through the notch depth. Figure 34 shows that depending on fiber angle, the strain measured at a point (for instance by a strain gage) will be above or below the average strain in the gage section. Hence the shear modulus calculated will be lower or higher than in actuality. In addition, the more popular 0° specimen (Figure 34b) has significant shear stress concentrations at the notch tips, indicating why in practice, the 0° specimen always fails at the notch tips.

Morton *et al.* [43] have studied in detail the differences between the 0° and 90° specimens. They showed that the 0° specimen is very sensitive to the actual locations of the loading points, which cannot be known accurately in the WF2. On the other hand, Morton *et al.* [43] showed that the 90° specimens are not sensitive to the loading point location. Therefore, the 90° is much less susceptible to errors in modulus readings due to misalignment in the fixture. However, they found that in the WF2, 90° specimens tend to twist, throwing off the strain readings. It was shown that in order to correct this behavior, both sides of the specimen need to be gaged, and the average strain from the two sides of the specimen determined. In this manner, the effects of twisting are negated and the strain in the gage section can be measured accurately [43].

Pindera *et al.* [54] and Morton *et al.* [43] showed that because the stress at the gage section is not equal to the average stress through the notch depth, a correction factor must be employed. Morton *et al.* [43] showed that while correction factors for the 0° specimen vary somewhat (because of the sensitivity to load point location), the correction factors for the 90° specimen can be calculated quite accurately, and that for the range of stiffnesses commonly found among advanced composites, this shear correction factor is only weakly dependent on G_{12}. Therefore, no iterative process need be used.

According to Morton *et al.* [43], when both sides of the Iosipescu specimen are gaged, and a correction factor is used, the 90° specimen can very accurately measure the shear modulus for a range of composite materials.

The 10° off-axis specimen is subjected to shear/extension coupling under uniaxial load. This causes stress concentrations at the grips if the ends of the coupon are rigidly clamped, as shown in Figure 35a. With conventional clamping methods, the complex loading produces large stress concentrations and associated errors in strength and modulus data. Chiao *et al.* [52] reported this to be the case with Kevlar®/epoxy laminates. Even when using the NASA grips [55] which allow the jaws to rotate, as in Figure 35b, the deflection is still not simple shear/extension (Figure 35c). Hence stress concentrations, although somewhat moderated, still exist. For short gage lengths, these stress concentrations will effect the modulus data as well as the strength data.

To avoid problems associated with coupling, the usual approach has been to make the specimen very long so that the test section is far removed from the end constraints. This practice will correct the modulus measurements, but because the stress concentrations still exist at the grips, the strength measurements will still be affected. Pindera *et al.* [54] found that for carbon/epoxy, the aspect ratio needs to be of the order of 20:1. This long specimen requires large amounts of material for property evaluation. For some time now a method has been sought that would allow the use of a shorter gage length (less material usage) and still give accurate data. Sun and Berreth [56] developed a new end tab which allows shear strain to develop, and thus simplifies the loading to something close to Figure 35c. In order to allow shearing of the coupon ends in the grips, a tab that has a very low in-plane shearing modulus is needed. Yet the tab must be substantial enough to grip the specimen adequately. After several materials were tried, it was found that a knitted glass impregnated with silicone rubber worked very well [56]. The glass provides the transverse stiffness for gripping the specimen, while the silicone allows in-plane shear deformations to occur. comparing results from strain gages located as per Figure 36, their studies showed that even with quite short aspect ratios (6:1) the new end tab virtually eliminates the stress concentrations due to clamping [56]. However, no subsequent work has been published in the literature concerning this end tab design.

Whitney *et al.* [57] concluded that the results for the rail shear test are valid provided that the length to width ratio of the gage section is 10 or more. They noted, however, that for certain laminates the stress distribution is quite irregular even with large aspect ratios. It was reported that the rail shear tests produce uniform stress fields only for laminates where the transverse stiffness is much greater than the shear stiffness. In other words, a 90° unidirectional specimen would have a uniform stress distribution, but a 0° unidirectional or a ±45° laminate would not, even with an aspect ratio of 10 to 1 [57]. This is a rather severe limitation given that ASTM recommends that the test can be used on either 0° or 90°, and on any symmetric or orthotropic laminate.

Bergner *et al.* [58] concluded that the rail shear test generates an area of uniform shear across the test section, but that high normal stresses accompany the shear depending on rail stiffness, method of loading and the laminate. Terry [48] states that even for 90° specimens the failure stress should be viewed with caution, since it is evident that at high strains, tensile loading of the fibers is present and contributes to apparent shear strength. In any case, there are significant stress concentrations in the corners, so failure is not initiated in the gage section. The specimen uses relatively large amounts of material, and the bonding or machining for bolt holes makes the specimen even more expensive.

The size of the cross beam specimen precludes its use when any number of tests must be run. As can be seen from Figure 28, the specimen uses large amounts of material and it is difficult to fabricate. Duggan *et al.* [49] found that significant stress concentrations exist at the corners, especially for $[\pm 45°]_S$ laminates. Errors of as much as 20% result from normal stresses present in the gage section in the maximum shear plane. Even if a moderate corner radius is left, the stress concentration remains large enough that failure still initiates at a corner.

The picture frame and panel shear specimens use substantial amounts of material, and the four bar frames are bulky and not easy to handle. The fabrication of sandwich panels for the picture frame is expensive, and the added work required to machine and reinforce the specimen adds further expense. Bryan [59] used photoelasticity and found that the actual stress state for the picture frame specimen varied significantly from pure shear.

The slotted tensile test was introduced by Duggan [49]. For ±45° laminates, the stress state was found to be much more ideal than the cross beam. In fact, Duggan reports that the strain gage results were within 2% of their calculated results [49]. When [0°/90°] laminates are used, the specimen fails in tension, not shear. The coupon itself is easy to fabricate, but the machining makes it more expensive than the ±45° tensile test. The main drawback is the necessity to introduce a controlled biaxial stress state by application of a second external force. In order to do this, a biaxial testing machine is needed.

These tests will be discussed in more detail in the conclusions section of this report. Some tests, such as the slotted tensile test and panel shear test will not be discussed because they are either too complex for general property evaluation, or they are inadequate in yielding strength and modulus data.

CHAPTER 5. CONCLUSIONS

In order to decide upon the test method which should be used for entering composite material properties into the CCMS database, it was necessary to establish some set of criteria against which each method could be judged. Lee and Munro [47] used such a technique when ranking shear tests. In this manner, certain aspects of the test can be weighted according to importance, and all tests for a certain property compared by the same standard. Because the tension, compression and shear tests are different in application and diversity of method, tests methods for each property have their own set of criteria against which they will be compared. It is recognized that the rating system employed herein is somewhat subjective in nature, but it is hoped that the results reflect the general opinion as far as possible. Opinions from the literature and industry contacts were considered for the purpose of rating in each area.

5.1. TENSION

While CRAG distinguishes between unidirectional and multidirectional tensile specimens, ASTM and SACMA do not. Effectively then, for multidirectional specimens all three test methods are roughly equivalent. The only real difference is that CRAG recommends the use of aluminum end tabs rather than glass/epoxy, as ASTM and SACMA recommend. Therefore, only the unidirectional specimens will be discussed, as there are some significant differences between the ASTM and SACMA specimens and the CRAG unidirectional specimen. See Figure 37. Since the ASTM and SACMA tests are so similar, any further reference to ASTM D 3039 will also include SACMA SRM 4.

In the composites industry in the United States, almost without exception the accepted method for testing tensile properties of composite materials is the ASTM D 3039 test. The only other widely accepted test method is the CRAG 3.1 tensile test used in Europe. The two types of coupon are significantly different, as has been discussed in chapter 2. Table 14 shows the criteria used to rate the unidirectional tensile tests, as well as the ratings of both the ASTM D 3039 and the CRAG 3.1 tests.

5.1.1 Specimen Material Quantity

Figure 37 shows the geometries of each coupon. Since all coupons use relatively small amounts of material, they were all were given maximum points.

5.1.2 Specimen Fabrication, Processing and Instrumentation

Both unidirectional specimens require some machining during the fabrication stage. See Figure 37. ASTM requires machining of end tab tapers, while CRAG requires machining of the waists for the gage section. CRAG 3.1 was scored lower than ASTM D 3039 because it was felt that improper machining of the waists was more likely to affect the property measurement than poorly machined end tabs. Hence the waists are more difficult to machine correctly than the taper for the fiberglass end tabs.

5.1.3 Uniformity of Stress/Strain Field

Both specimens scored high because as long as they are properly aligned in the grips, the stress/strain field for these types of specimen is quite uniform. Both specimens have gage lengths of sufficient length for St. Venant's principle to be satisfied.

5.1.4 Stiffness

Again, it has been discussed that the CRAG 3.1 test has been found to yield approximately 8% higher modulus values than the ASTM D 3039 unidirectional test [20]. This effect is probably due to the problems associated with machining away half of the CRAG 3.1 specimen [20]. ASTM D 3039 was given maximum points because it is generally accepted that modulus values are correct for this test.

5.1.5 Strength

It has already been discussed that the CRAG 3.1 test has been found to yield approximately 6% higher strength values than the ASTM D 3039 unidirectional test [20]. It is felt that this higher strength in the CRAG specimen may not be representative of the actual case because of statistical skewing due to short gage length, and perhaps other effects. Therefore CRAG 3.1 was rated below ASTM D 3039. Both specimens suffer from some stress concentrations, so neither will give wholly accurate strength measurements, and neither was awarded full points.

5.1.6 Scatter

For room temperature tests with no preconditioning, ASTM D 3039 usually yields relatively low coefficients of variation for both strength and modulus, typically of the order of 5% or less [14]. This is probably close to the variation in properties inherent in the material. However, Sottos reported that CRAG 3.1 showed variations of 14% for 0° tensile modulus. This is clearly not variation of the material. It indicates that the test itself is introducing significant scatter, which is unacceptable for a design test method. Accordingly, CRAG 3.1 was rated below ASTM D 3039.

5.2. COMPRESSION

The unidirectional compressive test is one of the most controversial tests for design allowables. There are those in academia and the aerospace manufacturing community who have expressed their opinion that there is no way to measure a compressive material property [25, 26]. The only thing that can be measured is some structural response that will depend upon the loading scheme, as well as the particular fixture used and the way in which the specimen is prepared. Nevertheless, whether the compressive properties are material properties or structural properties as has been suggested, some basis for comparison is needed for design purposes. Therefore, the best possible test should be selected even if it is not an ideal one.

Much research has been done to find an acceptable compressive test, or to improve existing test methods. In a survey given to several of the aerospace manufacturers and material suppliers, most of the respondents said that the 0° compressive test is the test most in need of development [27]. All of the commonly used compressive test methods can be grouped into three major categories, as follows:

- unsupported compression coupon
- supported compression coupon
- sandwich beams and columns

Unsupported compression coupon tests include the ASTM D 3410 Celanese and IITRI tests. Supported compression coupon tests include ASTM D 695, SACMA SRM 1 and many other face or edge supported coupon tests. There is also the ASTM D 3410 sandwich beam test.

In the aerospace industry, most design testing is done by ASTM D 3410 Celanese or IITRI [27]. However, depending on the demands of the contracting party, the ASTM D 3410 sandwich beam or SACMA SRM 1 may be specified as the design test [60]. Table 15 shows the criteria used for rating the unidirectional compressive tests, along with the individual test ratings. The face supported specimen in Table 15 refers to any of a number of commonly used modified ASTM D 695 tests such as SACMA SRM 1.

5.2.1 Specimen Material Quantity

Celanese, IITRI and SACMA SRM 1 coupons all use approximately the same amount of material, although SACMA SRM 1 recommends the use of two specimens; one used for modulus, and one for strength. Therefore, in order to obtain both properties, twice the amount of material must be used. All of these coupons (except the SACMA SRM 1 modulus coupon) require rather substantially sized end tabs, but generally the glass used for the tabs is less expensive than the graphite or Kevlar® that comprises the specimen.

On the other hand, the sandwich beam uses much more material than the other specimens. Not only does the sandwich specimen use at least 10 times more of the composite material, but the aluminum honeycomb represents a significant material cost also. The Celanese and IITRI specimens were both awarded full points. SACMA SRM 1 was rated somewhat lower due to the fact that twice as many specimens must be made. The sandwich specimens were rated significantly lower.

5.2.2 Specimen Fabrication, Processing and Instrumentation

Both the Celanese and IITRI specimens are very sensitive to irregularities on the faces of the end tabs. Therefore, the end tabs must be ground to close tolerances for flatness and parallelism [24]. In addition, the Celanese specimens must have close tolerances for the total thickness of specimen and end tabs. Improperly sized specimens can cause binding of the fixture (see Figure 38). Tolerances for the SACMA SRM 1 end tabs are not as critical as for the above two, but end tabs are still required. The sandwich specimens, however, are much more difficult to fabricate. Care must be taken to ensure that the face plates are adequately bonded over their entire surface, and that the cells of the honeycomb are at atmospheric pressure. Pressure deviations will result in either crushing of the honeycomb or bad bonds [30]. SACMA SRM 1 was rated highest, although full points were not assigned. Bonding and machining of the end tabs represents a significant cost. IITRI and Celanese followed and the sandwich structures were rated quite low due to the complexity and expense of their fabrication and processing.

5.2.3 Cost of Fixture

Figures 16-20 show the fixtures and specimens used for each test. Clearly the sandwich specimens rate highly as far as the fixture is concerned. The sandwich beam needs only to be loaded in four point bending. This simplicity of loading is one of the strengths of the sandwich type specimens. SACMA SRM 1 has a relatively simple fixture and can be made or purchased fairly inexpensively. Celanese and IITRI, however, require complicated and expensive fixtures. The sandwich specimens received full points and the SACMA SRM 1 was scored high, but due to high initial costs, the Celanese and IITRI fixtures were rated low. The expense for the fixtures is only a one-time cost, so this area was not weighted heavily.

5.2.4 Handling of Fixture, and Specimen Mounting

Some have criticized the Celanese and IITRI fixtures because they require long soak times for temperature testing, but this problem can be overcome by venting heated or cooled air past the specimen, removing the necessity for the fixture coming to thermal equilibrium also.

People who have used these fixtures have indicated that both fixtures are cumbersome to work with. The IITRI fixture weighs about 95 lbs. While the Celanese fixture is not nearly as heavy, it is still difficult to work with. The Celanese fixture also has an additional problem. The thickness of the specimen including end tabs has to be rather precise. If the specimen is too thick, line contact instead of surface contact will result between the conical grips and the fixture. This will affect modulus and strength readings, as additional friction and binding may occur [27]. See Figure 38. If the specimen is too thin, the fixture cannot provide gripping at all. Hence, only specimens of limited thickness can be tested in the Celanese fixture [27].

Both the sandwich specimens and the SACMA SRM 1 are straightforward as far as handling and mounting. They were accordingly rated highly, while Celanese and IITRI were rated lower.

5.2.5 Uniformity of Stress/strain Field

Clark and Lisagor [24] conducted a study of compressive test methods and included work on the uniformity of the strain field for three types of tests. They studied the IITRI unsupported coupon test, a face supported coupon test and an end loaded unsupported test. The uniformity of the strain field was checked by strain gages placed on the specimens to check for both out-of-plane and in-plane bending. Figure 39 shows the locations of strain gages used. Figure 40a shows a set of stress/strain curves for the IITRI fixture with an as-fabricated specimen (no grinding of the end tabs). Figure 40b shows typical stress/strain curves for an IITRI specimen with ground end tabs. Figure 40c shows a worst case set of stress strain curves for an IITRI specimen [24]. Clark and Lisagor indicate that typically, IITRI specimens exhibit uniform stress/strain fields [24]. Reiss *et al.* [32] studied the effect of perfect clamping constraints on the specimen, and found that, although quasi-isotropic layups suffer from some field non-uniformity, the non-uniformity due to clamping for unidirectional specimens should be confined to small regions at the corners of the gage section, away from strain gages [32]. Therefore, if the specimen and load axes are aligned properly and the end tabs are flat and parallel, both Celanese and IITRI unidirectional specimens should have relatively uniform stress/strain fields.

Clark and Lisagor [24] also reported uniformity of field data for a particular face supported fixture with strain gages located as per Figure 39. The specimen and fixture used in this study are shown in Figure 41, and typical stress/strain curves for the four gages are shown in Figure 42. It was noted that even with the face supports, there is a bifurcation of the curves, indicating that there is some sort of buckling taking place. This may lead to premature failure of the specimen. With such a long gage section, this result may not be surprising. Figure 42b shows a worst case set of stress/strain curves for the same fixture. It would appear that face supported fixtures are sensitive to lateral pressure which is usually regulated by bolt tightening.

One of the reasons the sandwich specimens were proposed was the hope that with a longer gage length and reduced stress concentrations and more uniform support against out-of-plane bending, the stress/strain field would be more uniform. In principle this is true. However, in practice, it is very difficult to reliably fabricate sandwich specimens. This is due to the sometimes non-ideal bond interface between the material to be tested and the honeycomb core. A certain percentage of specimens will suffer from these imperfections which will result in stress concentrations and perhaps delamination of the face from the core causing premature failure of the specimen [30].

Accordingly, the sandwich beam was rated low, as were face supported specimens. Unsupported gage length fixtures such as the Celanese and IITRI were rated higher, but still were not given full points because of the possibility of misalignment.

5.2.6 Stiffness

Abdallah [35] and others [24] have found that most compressive test methods will give accurate initial modulus values. Lamothe and Nunes [61] and others have noted that there is little or no difference between moduli found from the Celanese, IITRI and sandwich beam tests. Clark and Lisagor [24] noted that for quasi-isotropic layups, the secant moduli at 0.4% strain were comparable for face supported and IITRI fixtures, but that the face supported fixture had slightly higher moduli associated with it. There is always the possibility that face supported fixtures will bind because of the friction between the specimen and the supports [33], thus yielding slightly higher moduli.

Adsit [27] noted that if the specimen size for the Celanese is not correct, the fixture may deform enough to bind on the outer shell (see Figure 38). All specimens were rated high for modulus measurement.

5.2.7 Strength

There are substantial differences in strength values for the same material tested by different test methods. Virtually all methods suffer from some sort of stress concentration that will lead to conservative values for strength. Abdallah and others [35, 33] state that the Celanese, IITRI and sandwich beam methods all yield similar high strength results. Lamothe and Nunes [61] indicated that perhaps the Celanese fixture gave slightly lower strength values. Whitney and others [62, 24] showed that 0° side supported specimens yield strength data that is consistently lower than the unsupported specimens and the sandwich beam. It is generally felt that this is because of local instability associated with the longer gage length in a fully supported specimen [24]. Accordingly, the face supported fixtures were rated lower than the others.

5.2.8 Scatter

Clark and Lisagor [24] reported that the coefficient of variation in the data for the IITRI fixture is less than 9% for strength, and 5% for modulus. Berg and Adams [33] reported less than 5% variation for strength measurements using the IITRI fixture. Scatter for the sandwich beam is somewhat high because of the uncontrolable nature of the debonding problem. Lagace and Vizzini [30] noted that with sandwich-type specimens, the face can debond from the core causing premature failure.

It has been found that the SACMA SRM 1 compressive test method has relatively high scatter. Compression data presented to the MIL HDBK-17 Coordination Group [63] suggest that due to high coefficients of variation, this test may need to be re-evaluated.

Woolstencroft *et al.* [64] concluded that the compressive strength values measured by the Celanese and modified ASTM D 695 specimens had quite high coefficients of variation. Therefore, the face supported coupon was rated lowest, as well as the Celanese test, while IITRI and sandwich specimens were rated somewhat higher.

5.3. SHEAR

There are many test methods that have been proposed to characterize in-plane shear stress/ strain properties. This reflects the difficulty experienced in loading a specimen in pure shear.

According to a survey of aerospace industries [27], the most commonly used in-plane shear test is the ASTM D 3518 ±45° tensile test. Many researchers have also found encouraging results from the Iosipescu shear specimen, and ASTM is in the final stages of defining a test method for this specimen [44]. Table 16 shows the criteria used for rating the in-plane shear tests, along with the individual test ratings.

5.3.1 Specimen Material Quantity

Coupon specimens, including the two tensile and the Iosipescu specimens, use the least amount of material. Rail shear, crossbeam, picture frame and torsion tube specimens use substantially more material than the coupons. Each of them was rated accordingly.

5.3.2 Specimen Fabrication, Processing and Instrumentation

Coupon specimens are easiest to fabricate and handle. The 10° off-axis specimen requires more time, since it is usually made by cutting a unidirectional 0° panel at a 10° angle. The angle needs to be within 1° so the results are not affected. The Iosipescu requires the additional step of machining the "V" notches, with close tolerances on the notch radius. In addition, according to Morton *et al.* [43], the Iosipescu specimen needs to be gaged on both sides. The rail shear specimen requires either drilling holes or bonding the rails on, which requires considerably more fabrication time than the coupons. Sandwich specimens such as the picture frame and crossbeam necessitate even more fabrication time. The torsion tube is quite expensive and difficult to make and it requires great precision in the fabrication process. In addition, the torsion tube may require several strain gages per specimen to check for uniformity of the stress field and evidence of buckling.

5.3.3 Cost of Fixtures

One of the big advantages of the ±45° tensile test is that no fixture is required. It can be performed on a standard tensile machine even without bonded end tabs. The 10° off-axis tensile test can also be performed without a fixture, but in order to reduce stress concentrations, rotating grips may need to be employed. The torsion tube does not require a fixture either, but it must be tested in a torsion machine, rather than a standard test machine. The cross beam needs only to be loaded in bending. While this is not quite as easy a test to perform as the tensile coupon tests, a relatively inexpensive fixture can be used in this test. The picture frame and rail shear fixtures are relatively expensive. The Iosipescu specimen is usually tested in either an antisymmetric four point bending fixture (AFPB) [41] or in the Modified Wyoming fixture (WF2) [64]. The cost of an AFPB fixture would be less than a WF2 fixture.

5.3.4 Non-Standard Test Equipment

The only test that requires non-standard equipment is the torsion tube. The test requires a torsion machine that has the capability of keeping the axial and transverse loads near zero. This represents a significant cost, as many laboratories are not equipped with such a machine.

5.3.5 Handling of Fixture and Specimen Mounting

The ±45° and 10° off-axis tensile and the Iosipescu specimen are all very easy tests to perform. The specimen is simply mounted in either the testing machine grips, or in the case of the Iosipescu, placed in the fixture and secured. The Picture frame and rail shear both have more complicated specimen mounting procedures which include either bonding rails onto the specimen or bolting the specimen into the fixture. The torsion tube, as mentioned before is quite a complicated test to perform.

5.3.6 Uniformity of Stress/Strain Field

It is understood through the mechanics of the problem that a state of pure shear cannot be achieved in the ±45° specimen. Normal stresses exist in the plane of maximum shear, but it is assumed that because of the presence of orthogonal fibers, the normal stresses will not affect shear strength measurements. Terry [48] stated that for the ±45° specimen, the edge effects tending to cause premature failure are minimal as long as the stacking sequence is as homogeneous as possible. Most ±45° tests, however, are fabricated with a $[\pm 45°]_{ns}$ stacking sequence [18, 19]. This places two identical plies together in the center and may allow edge effects to become important. More importantly, Kellas and Morton [51] have shown that the mid-plane ply thickness relative to the laminate thickness is a very important factor which controls both the shear strength and stress/strain response. Therefore, the stress uniformity of the ±45° test is dep on the stacking sequence chosen. ASTM specifies no stacking sequence, and SACMA specifies a $[\pm 45°]_{2S}$, which has been shown to have low shear strengths compared to a $[\pm 45°]_{4S}$ laminate [51]. However, according to Kellas and Morton [51], this test can be improved if the effect of ply blocking is reduced by testing a specimen whose stacking sequence is $[\pm 45°]_{ns}$ where $n \geq 6$. See Figure 32.

The 10° off-axis test is adversely affected by a pronounced shear/extension coupling. This has been noted by Chiao *et al.* [52], Pindera *et al.* [54] and others. In order to partially alleviate the problem, very high aspect ratio (≥15 to 1) specimens must be used [54]. Even in this case, the field is not uniform due to tensile stresses normal to the fibers. These normal tensile stresses may become important in the ultimate failure of the material, since normal to the fibers, the composite is very weak. Pindera *et al.* [54] advocated the use of correction factors in order to account for the actual and apparent modulus. These correction factors, however, are functions of the shear modulus, so an iterative process may have to be employed.

Many researchers have studied the Iosipescu test [43, 42, 65, 66]. Both numerical and experimental results show that the stresses through the notch of the specimen are not strictly ideal. Normal stresses present in the gage section are insignificant, but with highly orthotropic materials, shear stress concentrations exist at the notches [66]. On the basis of the findings Walrath and Adams [65], a new specimen and fixture were developed, and these are used by many researchers. Morton *et al.* [43] found, however, that significant non-uniformities still exist for 0° specimens. They showed that there are significant differences between 0° and 90° specimens (see Figures 34 and 45). Using a 90° specimen resulted in a more accurate determination of the shear strains. Because the stress is non-uniform, the stress in the gage section is not equal to the average stress applied. However, shear correction factors developed for the 90° specimen were found not to be sensitive to the shear modulus itself (within the range of stiffness of advanced composites) [43]. Therefore, no iteration is necessary to find an accurate shear modulus. However, according to Morton *et al.* [43], this specimen is unsuitable for shear strength measurements

The rail shear test has been studied by Whitney *et al.* [57]. They concluded that for 90° specimens, the stress/strain distribution is uniform a short distance from the edge for aspect ratios ≥ 10. However, for ±45° and 0° rail shear specimens, the shear stress distribution is very irregular across the gage section, leading to low shear strength measurements [57]. Garcia [67] concluded that in 0° specimens, very large normal stresses occur perpendicular to the fibers and initiate premature failure. Sims [46] believed that the 3 rail shear test better approximated pure shear but Bergner [58] found that significant normal stresses often still accompany the region of uniform shear. In all cases, significant stress concentrations exist at the corners.

Regarding the cross beam, Herakovich *et al.* [66] state that normal stresses are very small for $[0°/90°]_{ns}$ specimens, and that the stress state is pure and uniform shear in the gage section. However, the corners experience large stress concentrations, causing premature failure. Duggan *et al.* [49] showed that depending on choice of core material and fiber orientation, the stress state can deviate considerably from pure shear. For example, a $[\pm45°]_{ns}$ specimen has large normal stresses in the gage section resulting in errors of 13 to 20% in strength measurements.

Bryan [59] found that for the picture frame specimen, the stress distribution deviates significantly from pure shear, and that the method is inappropriate for in-plane modulus measurement.

By the nature of the loading in the torsion tube, pure and uniform shear stress results around the circumference and along the length of the gage section. Since the thickness of the tube walls is kept small, stress variations through the thickness are negligible [47]. Stress concentrations may result from the gripping method [68].

The torsion tube test was given full points because when performed correctly, pure and uniform shear can be achieved in the entire gage section. The 90° Iosipescu was rated highly because with both sides of the specimen gaged, and shear correction factors used, the state of strain in the specimen can be accurately characterized. The ±45° tensile and 10° off-axis tests both have non-uniform shear stress distributions, and were rated somewhat lower. Both the rail shear and cross beam specimens may or may not have uniform stress distributions depending on fiber angle and other parameters, so they were rated somewhat also. The picture frame test is simply not fit for modulus readings.

5.3.7 Direct/Indirect Property Measurement

Both the ±45° tensile and the 10° off-axis specimens are loaded in tension and their shear properties are backed out according to orthogonal transformations. All other specimens are loaded in direct shear. In addition, the 10° off-axis test requires the longitudinal stiffnesses E_1 and E_2 as input before G_{12} can be calculated. This is also true of the Iosipescu specimen if the shear correction factors are to be calculated [43].

5.3.8 Stiffness

Chiao *et al.* [52] compared the ±45° tensile test, the 10° off-axis test and the torsion tube. Figure 43 shows their results. They found that at 0.5% strain, the ±45° tensile test yields a shear modulus 10% higher than the torsion tube. The 10° off-axis specimen yielded modulus readings that were 19% higher than the torsion tube. Due to the constrained ends of the 10° off-axis specimen and the shear/extension coupling, even a coupon with an aspect ratio of 20, such as the one used here, gives high modulus readings.

Morton *et al.* [43] have shown that when certain precautions are taken and appropriate correction factors used, the 90° Iosipescu is quite accurate for measuring shear modulus. Whitney *et al.* [57] concluded that the rail shear can be used to accurately measure shear modulus provided the aspect ratio of the test section is ≥10 and a 90° specimen is used.

Herakovich *et al.* [66] stated that the cross beam yields satisfactory results for stiffness. As noted before, Bryan [59] stated that the panel shear method cannot be used for modulus readings. Accordingly, the panel shear and the 10° off-axis tests were not rated highly, whereas all other methods were given near maximum points.

5.3.9 Strength

Chiao *et al.* [52] reported that the ±45° test gave shear strengths about 6% lower than the torsion tube. However, Kellas and Morton [3] and [51] found that strength from the ±45° test varies with stacking sequence, and that it is unclear how strength data should be reduced for this test.

The 10° off-axis test yielded strengths about 38% lower than the torsion tube [52].

Morton *et al.* [43] reported that while modulus correction factors for the Iosipescu test can be found using finite element analysis, it is unclear how to correct for shear strength data. Swanson compared results from a 0° Iosipescu test and the torsion tube. Figure 44 shows his results. He claims that the horizontal steps on the stress/strain curve correspond to initiation of cracks along the fibers in the 0° specimen. Taking the onset of cracking to mean shear failure, the strength data compare favorably with that of the torsion tube. However, other researchers have not noted this same axial splitting phenomenon until much higher strains [43, 54]. Pindera *et al.* [54] and Morton *et al.* [43] also reported that failure stress of a 90° Iosipescu test are substantially lower than for 0° specimens, even though in theory the two cases should be identical. Figure 45 shows results from Morton *et al.* [43] and Figure 46 shows the results of Pindera *et al.* [54] comparing 0° and 90° Iosipescu, along with the 10° off-axis and a 45° off-axis test.

Whitney *et al.* [57] concluded that the rail shear test can be used for ply strength if 90° specimens are used, although somewhat conservative values will result because of the stress concentrations at the corners. 0° specimens have a very irregular stress field leading to low strength data.

The cross beam and picture frame both suffer from large stress concentrations at the corners. They are not recommended for strength measurements.

5.3.10 Scatter

Chiao *et al.* [52] reported coefficients of variation of less than 5% (both strength and modulus) for the ±45° tensile, the 10° off-axis and the torsion tube. Swanson reported a coefficient of variation for the 0° Iosipescu of less than 10%, while Morton *et al.* [43] state that using the 90° Iosipescu and proper procedures, coefficients of variation for shear modulus are very low. Rail shear scatter is relatively low. However, the picture frame and cross beam have somewhat higher scatter. They were therefore rated lower than the other tests.

5.4. RECOMMENDATIONS

Although there may not be an ideal choice for compression and shear test methods, a choice must be made in order to initiate the implementation of the CCMS database. Further refining of the guidelines must be addressed in the future, and the database will have to be modified accordingly. As can be seen from Tables 14-16, the choices for test methods for tension, compression and shear are as follows:

1. Uniaxial tension - - ASTM D 3039 tensile
2. Uniaxial compression - - ASTM D 3410 IITRI
3. In-plane shear - - ASTM D 3518 ±45° tensile

Some qualifications must accompany these choices for test methods. First, it would be best to have a mean value for uniaxial tensile strength that includes grip failures at or above the average gage section failure. It is fairly clear that the unidirectional tensile test as defined by ASTM and SACMA is adequate in characterizing advanced composites, although there may be some room for modification. Second, because of the ambiguity in compressive strength caused by different failure modes, the mode in which the specimens fail must be indicated when properties are reported. And third, the ±45° laminates must have a stacking sequence where the effect of ply blocking is minimized, such as $[\pm 45°]_{ns}$ where $n \geq 6$. This is according to Kellas and Morton's [51] finding that $[\pm 45°]_{2s}$ laminates have significantly lower shear strengths due to relative ply thickness effects.

Several conclusions can be drawn from the information presented in this report. First, it may be helpful to modify the standard recommendations for the ASTM D 3039 tensile test. For example, issues such as the need for end tabs, the inclusion in the mean property calculation of grip failures at or above the mean gage section failure, and end tabs for laminates with shear/extension coupling (like that proposed by Sun and Berreth [56]) may benefit from further consideration and study. Second, there is no ideal compression test. ASTM D 3410 IITRI is only the best choice of several tests that are not quite adequate for advanced composite compressive characterization. Third, as stated by Morton *et al.* [43], the Iosipescu specimen needs to be further studied in order to determine if there is any way to obtain both shear modulus and shear strength from this method.

It is therefore proposed that a follow-up study be done, wherein individual test methods are analyzed in more detail. Both experimental and numerical techniques should be employed to determine the usefulness of several candidate tests for given applications. The ultimate objective of the proposed study will be to refine existing test methods and/or propose new ones. The two areas in which such research is needed are in-plane shear and uniaxial compression.

Using extreme experimental conditions and material systems, existing test methods, where appropriate, will be analyzed in order to assess the following:

- Uniformity of stress/strain field,
- Repeatability of the results,
- Accuracy of the results,
- Type of instrumentation required,
- Applicability of the test to different materials and environments, and
- Possibility of improving a method.

Methods of analysis will include finite element modeling, and comparison with high sensitivity moiré full-field strain measurement. In addition, other issues, such as the ease of performing the test, cost of specimen fabrication, etc., will be considered.

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Table 1. Variability of data.

Specimen	X_1 (ksi)	Group	$\overline{X}_1$ (ksi)	Variation from mean* (%)	Standard Deviation
1 2 3 4 5	356 271 296 270 347	a	308	+2.7	41.2
6 7 8 9 10	261 365 279 338 317	b	312	+4.0	42.4
11 12 13 14 15	257 294 267 332 250	c	280	-6.7	33.5
		All 15 specimens [15]	300*	– –	39.2

Table 2. ASTM standard tests [17].

	ASTM Test	Description	Specimen type
Tension	D 2290	Test method for apparent tensile strength of ring or tubular plastics and reinforced plastics by split disk method	ring
	D 3039	Test method for tensile properties of fiber-resin composites	rectangular coupon
	D 3552	Test method for tensile properties of fiber-reinforced metal matrix composites	rectangular coupon
	D 3479	Test methods for tension-tension fatigue of oriented fiber-resin composites	plain rectangular specimen
Compression	D 3410	Test method for compressive properties of unidirectional or crossply fiber-resin composites	rectangular coupon or sandwich beam
	D 695	Test method for compressive properties of rigid plastics	wasted coupon
Shear	D 3518	Practice for in-plane shear stress-strain response of unidirectional reinforced plastics	±45° rectangular specimen
	D 2344	Test method for apparent interlaminar shear strength of parallel fiber composites by short-beam method	short beam
	D 4255	Test method for in-plane shear stress-strain response of unidirectional or symmetric laminated reinforced plastics by 2- or 3-rail shear method	rectangular panel

Table 3. SACMA recommended tests [18].

	SACMA Test	Description	Specimen type
Tension	SRM 4	Test method for tensile properties of oriented fiber-resin composites	rectangular coupon
	SRM 5	Test method for open hole tensile properties of oriented fiber-resin composites	notched rectangular coupon
Compression	SRM 1	Test method for compressive properties of oriented fiber-resin composites	rectangular coupon
	SRM 3	Test method for open hole compression properties of oriented fiber-resin composites	notched rectangular coupon
Shear	SRM 7	Test method for inplane shear stress-strain properties of oriented fiber-resin composites	±45° rectangular coupon
	SRM 8	Test method for apparent interlaminar shear strength of oriented fiber-resin composites by the short beam method	short beam

Table 4. CRAG recommended tests [19].

	CRAG Test	Description	Specimen type
Tension	3.1	Longitudinal tensile test for unidirectional CFRP, GRP, KRP	wasted rectangular coupon
	3.2	Tensile test for multi-directional laminates of CFRP, GRP, KRP	rectangular coupon
	3.3	Notched Tensile test for multi-directional laminates of CFRP, GRP, KRP	notched rectangular coupon
Compression	4.1	Longitudinal compression properties: unidirectional CFRP, GRP, KRP	celanese fixture, rectangular coupon
	4.2	Longitudinal compression properties: multi-directional laminates of CFRP, GRP, KRP - plain specimens	celanese fixture, rectangular coupon
	4.3	Longitudinal compression properties: multi-directional laminates of CFRP, GRP, KRP - notched specimens	celanese fixture rectangular coupon
Shear	2.1	Interlaminar shear strength test for CFRP, GRP, KRP	three-point bending, rectangular coupon
	5.1	In-plane shear Properties of CFRP, GRP, KRP	±45° rectangular coupon

Table 5. Tests now pending or under consideration by ASTM.

Test	Description	Specimen type
Iosipescu	Test method for in-plane and interlaminar shear modulus and strength of fiber-resin composites	double V notched coupon [47, 54]
Compression after impact	Test method for compression properties of damaged fiber-resin composites	rectangular coupon [21]
Fracture toughness	Test method for characterizing the damage tolerance of fiber-resin composites	double cantilever beam [21]

Table 6. Standard tensile tests.

test	Description	Specimen type	Restrictions
ASTM D 638 [17]	Test method for tensile properties of engineering materials	dogbone coupon	– –
ASTM D 3039 [17]	Test method for tensile properties of fiber-resin composites	rectangular coupon	modulus>20 GPa (>3 x 10^6 psi)
SACMA SRM 4 [18]	Test method for tensile properties of oriented fiber-resin composites	rectangular coupon	modulus>3 x 10^6 psi
CRAG 3.1 [19]	Longitudinal tensile test for unidirectional CFRP, GRP, KRP	waisted rectangular coupon	Unidirectional CFRP, GRP or KRP
CRAG 3.2 [19]	Tensile test for multi-directional laminates of CFRP, GRP, KRP	rectangular coupon	CFRP, GRP or KRP

Table 7. ASTM standard compressive tests [17].

ASTM Test	Description	Specimen type	Restrictions
D 3410 Celanese	Test method for compressive properties of unidirectional or crossply fiber-resin composites	rectangular coupon shear loaded	modulus>20 GPa (>3 x 10^6 psi)
D 3410 IITRI	Test method for compressive properties of unidirectional or crossply fiber-resin composites	rectangular coupon shear loaded	modulus>20 GPa (>3 x 10^6 psi)
D 3410 sandwich	Test method for compressive properties of unidirectional or crossply fiber-resin composites	sandwich beam	modulus>20 GPa (>3 x 10^6 psi)
D 695	Test method for compressive properties of rigid plastics	waisted coupon, end loaded, face supports	– –

Table 8. SACMA recommended compressive tests [18].

CRAG Test	Description	Specimen type	Restrictions
SRM 1	Test method for compressive properties of oriented fiber-resin composites	rect. coupon, end loaded, face supports	modulus>3 x 10^6 psi
SRM 2	Test method for compression after impact properties of oriented fiber-resin composites	rect. coupon, end loaded, edge supports	modulus>3 x 10^6 psi
SRM 3	Test method for open-hole compression properties of oriented fiber-resin composites	notched coupon, end loaded, face supports	modulus>3 x 10^6 psi

Table 9. CRAG recommended compressive tests [19].

CRAG Test	Description	Specimen type	Restrictions
4.1 Celanese	Test method for compressive properties of unidirectional CFRP, GRP and KRP	rectangular coupon shear loaded	unidir. or crossply CFRP, GRP or KRP
4.2	Test method for compressive properties of multidirectional laminates of CFRP, GRP and KRP	rect. coupon, end loaded, face supports	CFRP, GRP or KRP
4.3	Test method for compressive properties of multidirectional laminates of CFRP, GRP and KRP - notched specimens	notched coupon, face supports	CFRP, GRP or KRP

Table 10. ASTM standard and recommended shear tests [17].

ASTM Test	Description	Specimen type	Restrictions
D 3518	Practice for in-plane shear stress-strain response of unidirectional reinforced Plastics	±45° rectangular coupon	modulus>20 GPa (>3 x 10^6 psi)
D 4255	Test method for in-plane shear stress-strain response of unidirectional or symmetric laminated reinforced plastics by 2- or 3-rail shear method	rectangular panel	modulus>20 GPa (>3 x 10^6 psi)
D 2344	Test method for apparent interlaminar shear strength of parallel fiber composites by the short-beam method	short beam in 3-point bending	modulus>20 GPa (>3 x 10^6 psi)

Table 11. SACMA recommended shear tests [18].

SACMA Test	Description	Specimen type	Restrictions
SRM 7	Test method for in-plane shear properties of CFRP, GRP and KRP	±45° rectangular coupon	modulus>3 x 10^6 psi
SRM 8	Test method for interlaminar shear strength for CFRP, GRP and KRP	short beam in 3-point bending	modulus>3 x 10^6 psi

Table 12. CRAG recommended shear tests [19].

CRAG Test	Description	Specimen type	Restrictions
5.1	Test method for in-plane shear properties of CFRP, GRP and KRP	±45° rectangular coupon	CFRP, GRP or KRP
2.1	Test method for interlaminar shear strength for CFRP, GRP and KRP	short beam in 3-point bending	CFRP, GRP or KRP

Table 13. Other proposed shear tests.

Test [ref]	Description	Specimen type	References
Torsion tube	Test method for in-plane shear properties of unidirectional fiber-resin composites	hoop wound tube	[68, 69]
Torsion rod	Test method for in-plane shear properties of unidirectional fiber-resin composites	rod or bar	- -
Iosipescu	Test method for in-plane shear properties of arbitrarily laminated fiber-resin composites	double V notched specimen	[44, 65]
10° off-axis tension	Test method for in-plane shear properties of unidirectional fiber-resin composites	rect. tensile coupon, 10° fiber angle	[45, 54]
Cross beam	Test method for in-plane shear properties of cross-ply fiber-resin composites	sandwich cross beam	[49]
Picture frame	Test method for in-plane shear properties of arbitrarily laminated fiber-resin composites	flat panel	[59, 70]
Panel shear	Test method for in-plane shear properties of arbitrarily laminated fiber-resin composites	flat panel	- -
Slotted tensile	Test method for in-plane shear properties of unidirectional fiber-resin composites	slotted tensile coupon	[49]

Table 14. Criteria for rating unidirectional tensile tests.

Aspect of Test	Points Possible	ASTM D 3039*	CRAG 3.1
Cost of Specimen:			
• material quantity	75	75	75
• fabrication, processing and instrumentation	75	70	65
Theory/Experiment Agreement			
• uniformity of stress/strain field	200	200	200
Accuracy of Results			
• stiffness	200	200	180
• strength	200	180	170
Repeatability of Results			
• scatter	250	240	220
Total	1000	965	910

*also SACMA SRM 4

Table 15. Criteria for rating unidirectional compressive tests.

Aspect of Test	Points Possible	Celanese	IITRI	Sandwich beam	Face support
Cost of Specimen:					
• material quantity	**50**	50	50	10	40
• fabrication, processing and instrumentation	**50**	30	35	10	45
Cost of Test:					
• fixture	**50**	20	20	50	45
Ease of Test					
• handling of fixture, and specimen mounting	**100**	70	70	100	90
Theory/Experiment Agreement					
• uniformity of stress/strain field	**175**	150	150	140	100
Accuracy of Results					
• stiffness	**175**	170	175	175	165
• strength	**175**	165	170	170	140
Repeatability of Results					
• scatter	**225**	180	200	200	180
Total	**1000**	835	870	855	805

Table 16. Criteria for rating in-plane shear tests.

Aspect of Test	Points Possible	±45° tensile	10° off-axis	90° Iosipescu	rail shear	cross beam	picture frame	torsion tube
Cost of Specimen:								
• material quantity	**50**	50	50	50	30	5	5	20
• fabrication, processing and instrumentation	**50**	50	45	40	30	5	10	5
Cost of Test:								
• fixtures	**50**	50	50	35	40	45	40	50
• non-standard test equipment	**50**	50	50	50	50	50	50	0
Ease of Test								
• handling of fixture and specimen mounting	**100**	100	100	100	75	95	75	50
Theory/Experiment Agreement								
• uniformity of stress/strain field	**150**	130	100	140	100	100	50	150
Data Processing								
• direct/indirect properties measurement	**50**	25	25	25	50	50	50	50
Accuracy of Results								
• stiffness	**150**	140	120	145	145	145	100	150
• strength	**150**	120	100	110	130	120	110	145
Repeatability of Results								
• scatter	**200**	190	190	185	190	170	170	190
Total	**1000**	**905**	**830**	**880**	**840**	**785**	**660**	**810**

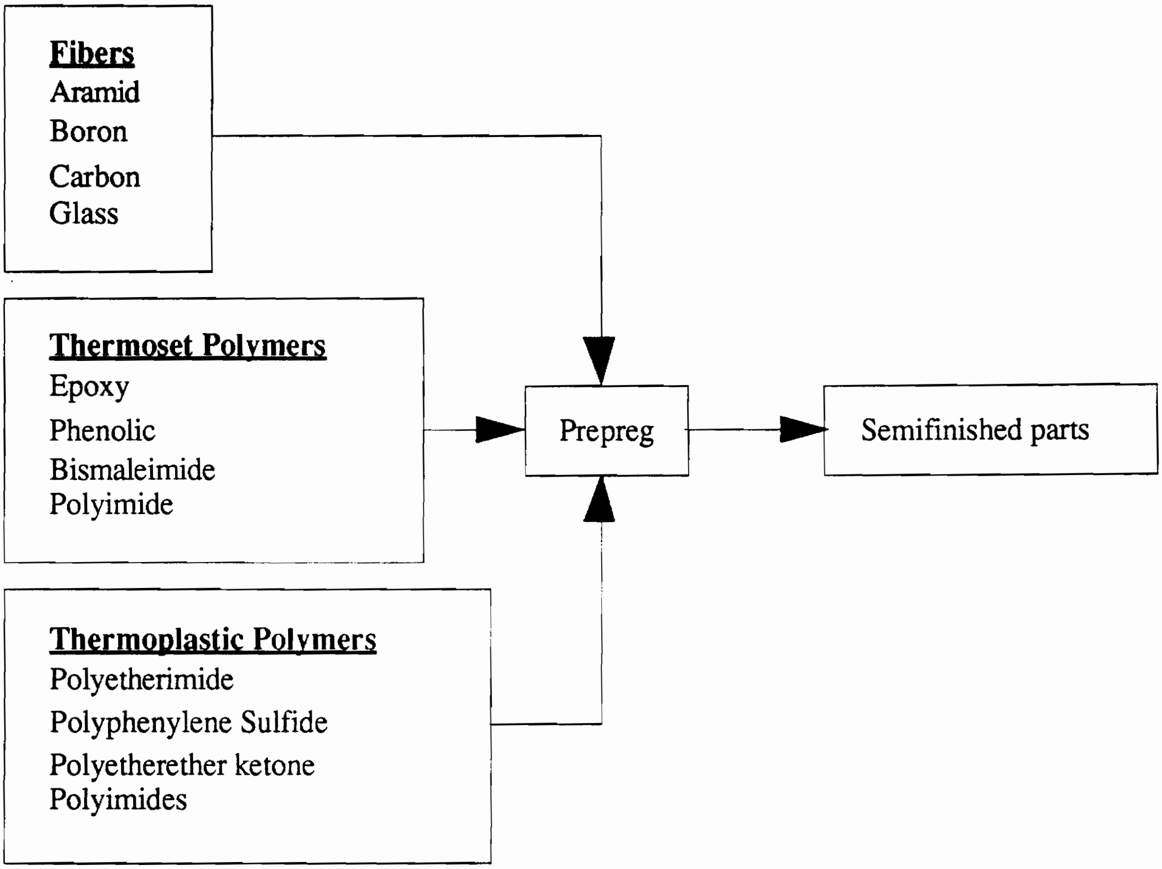


Figure 1. Definition of advanced composite materials [1]

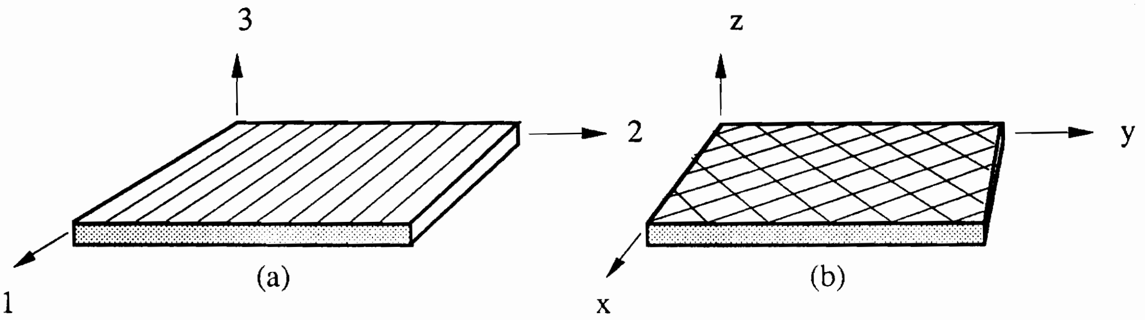


Figure 2. **Principal directions of a lamina (a) and a laminate (b).**

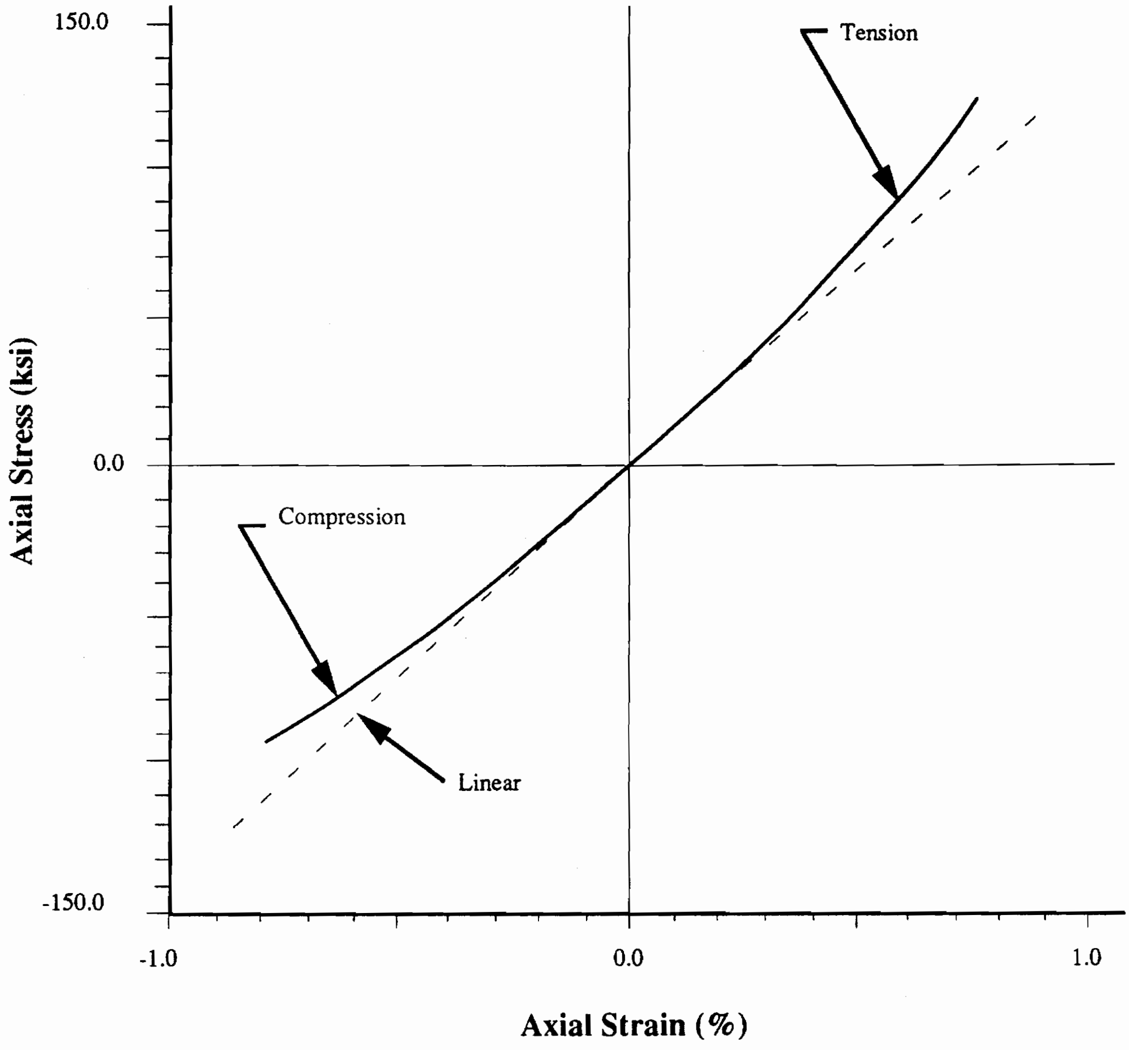


Figure 3. Non-linear stress/strain behavior of unidirectional composites [5].

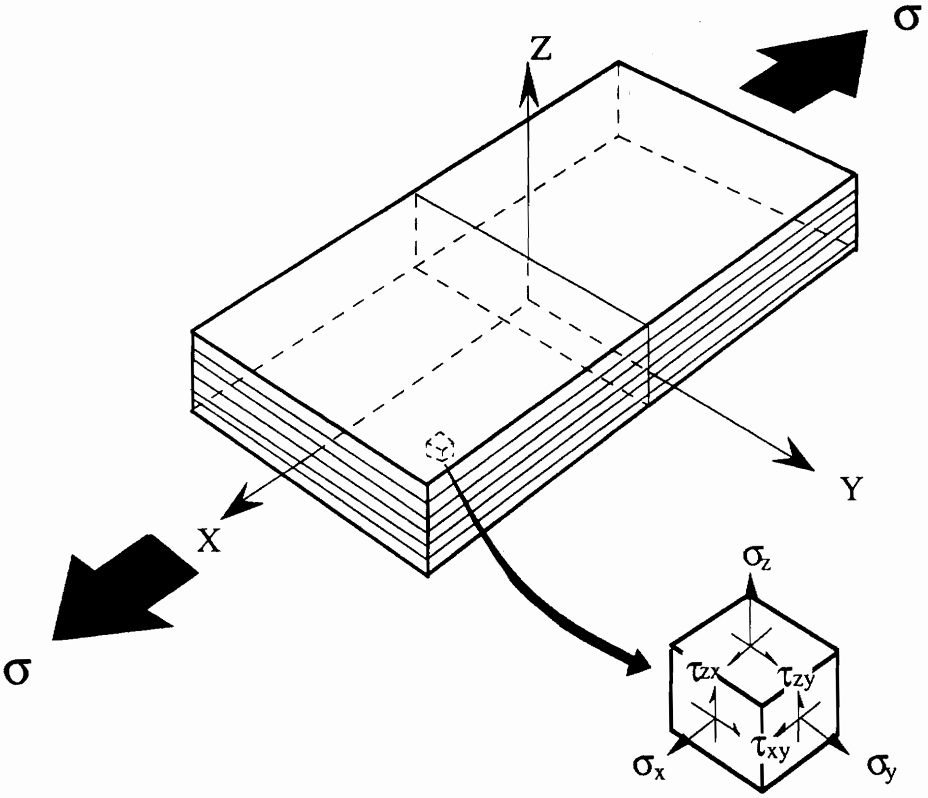


Figure 4. Free-edge effects [2].

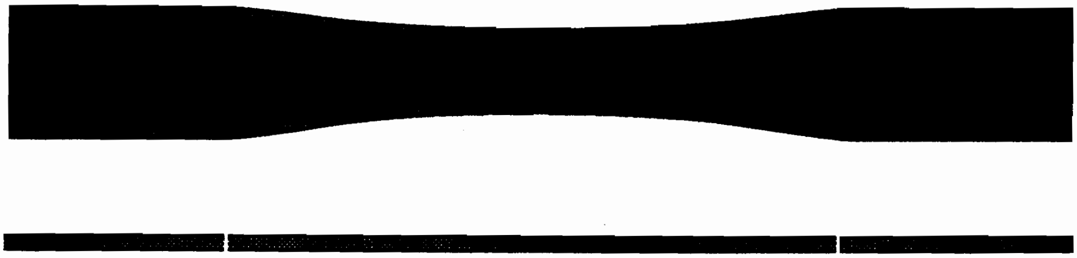


Figure 5. ASTM D 638 dogbone specimen.

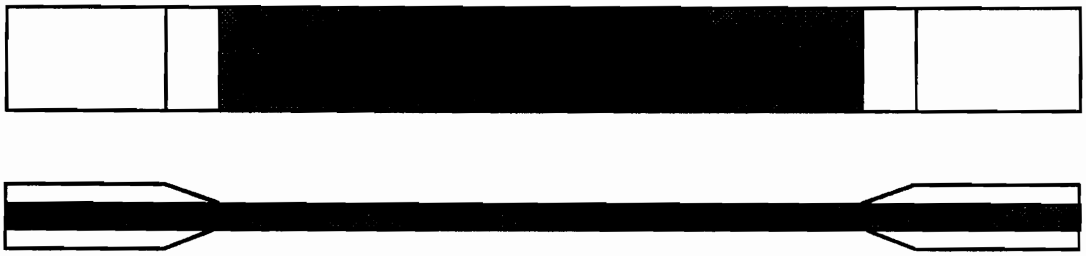


Figure 6. ASTM D 3039 coupon.

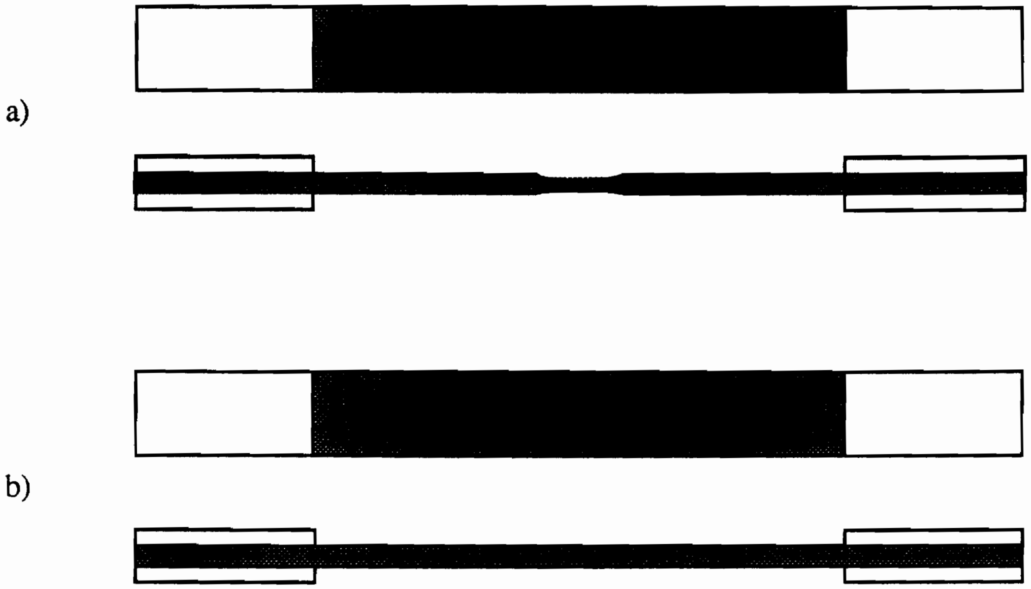


Figure 7. CRAG 3.1 unidirectional (a) and 3.2 multidirectional (b) coupons.

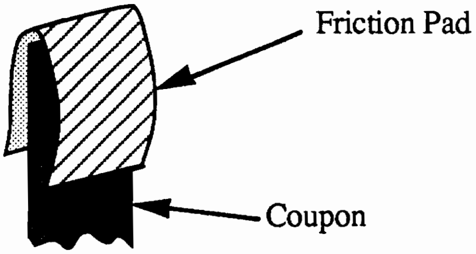


Figure 8. Friction pad grip arrangement.

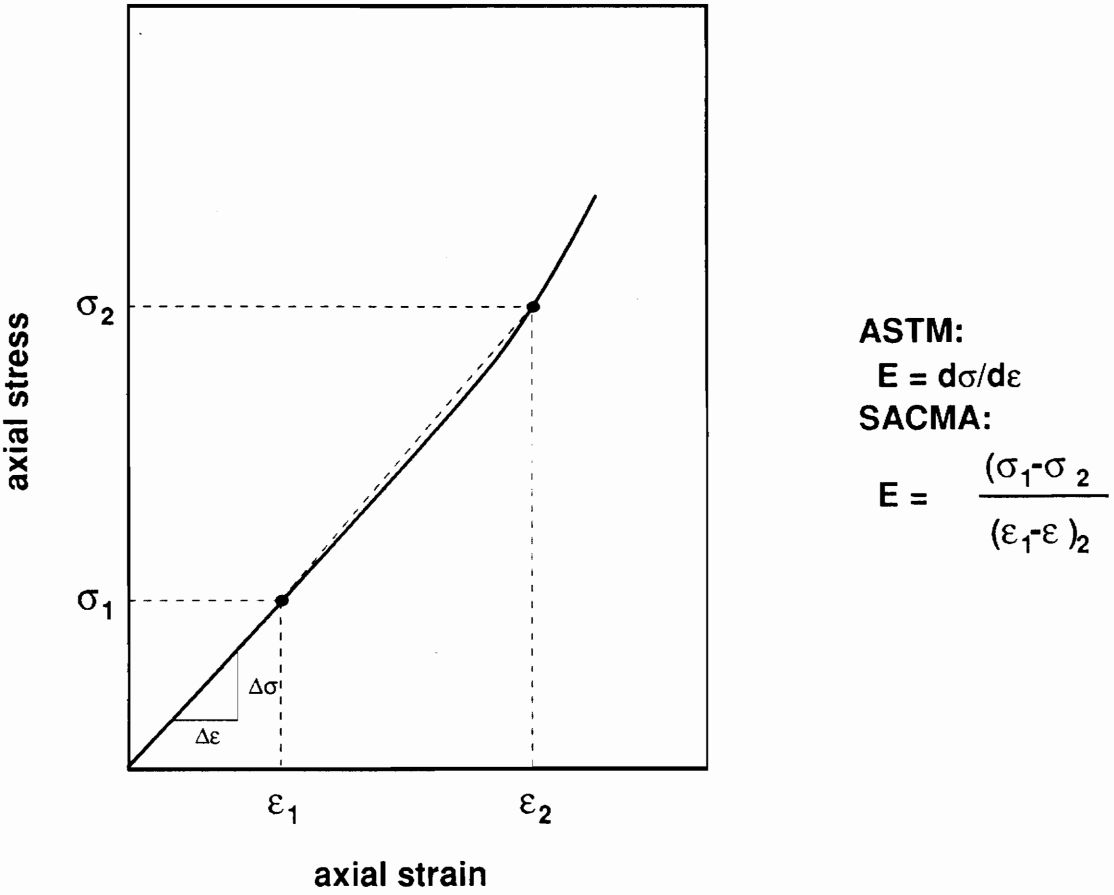


Figure 9. Difference in data reduction between ASTM and SACMA [17, 18].

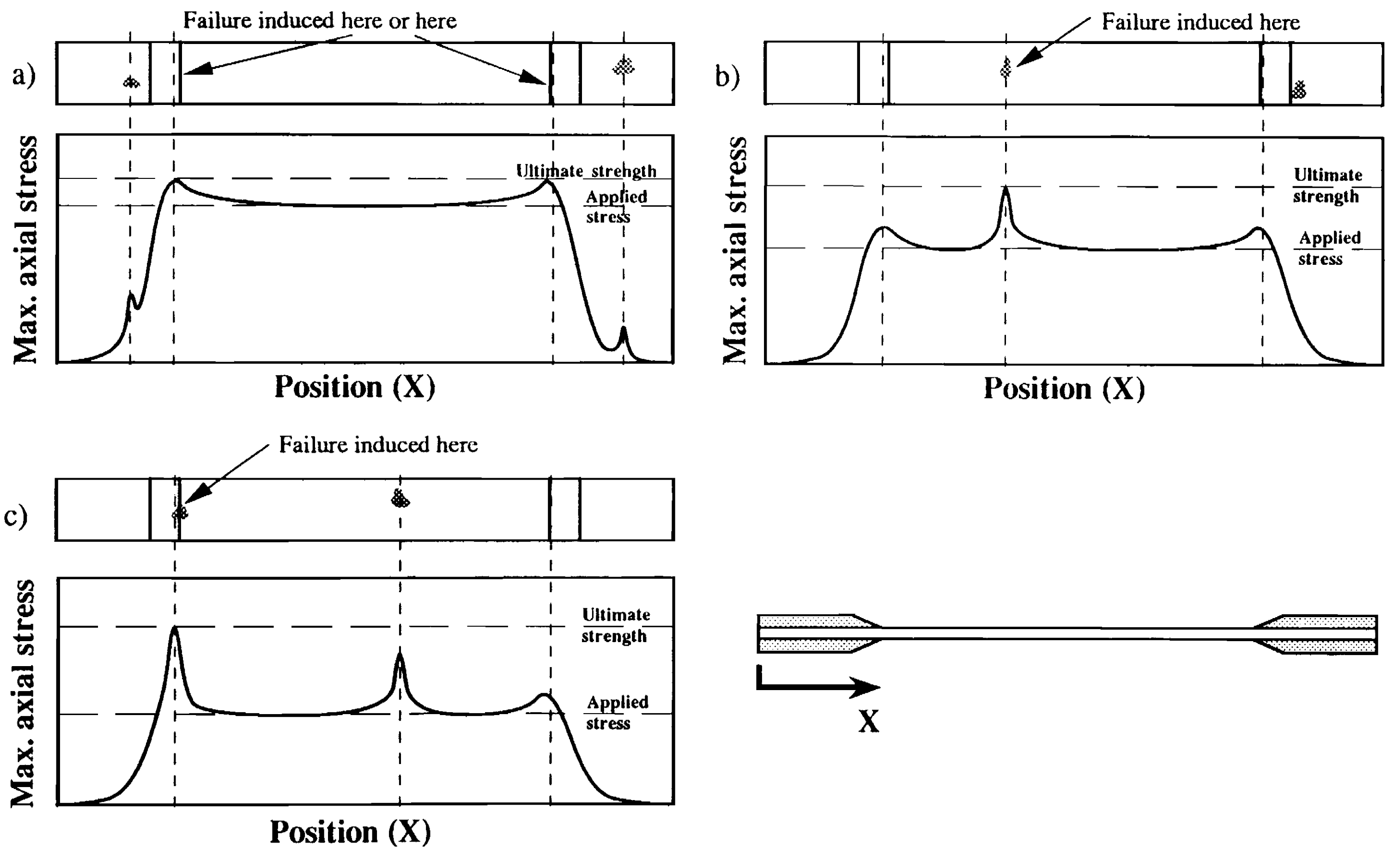


Figure 10. Schematic of maximum axial stresses in ASTM D 3039 coupons containing flaws.

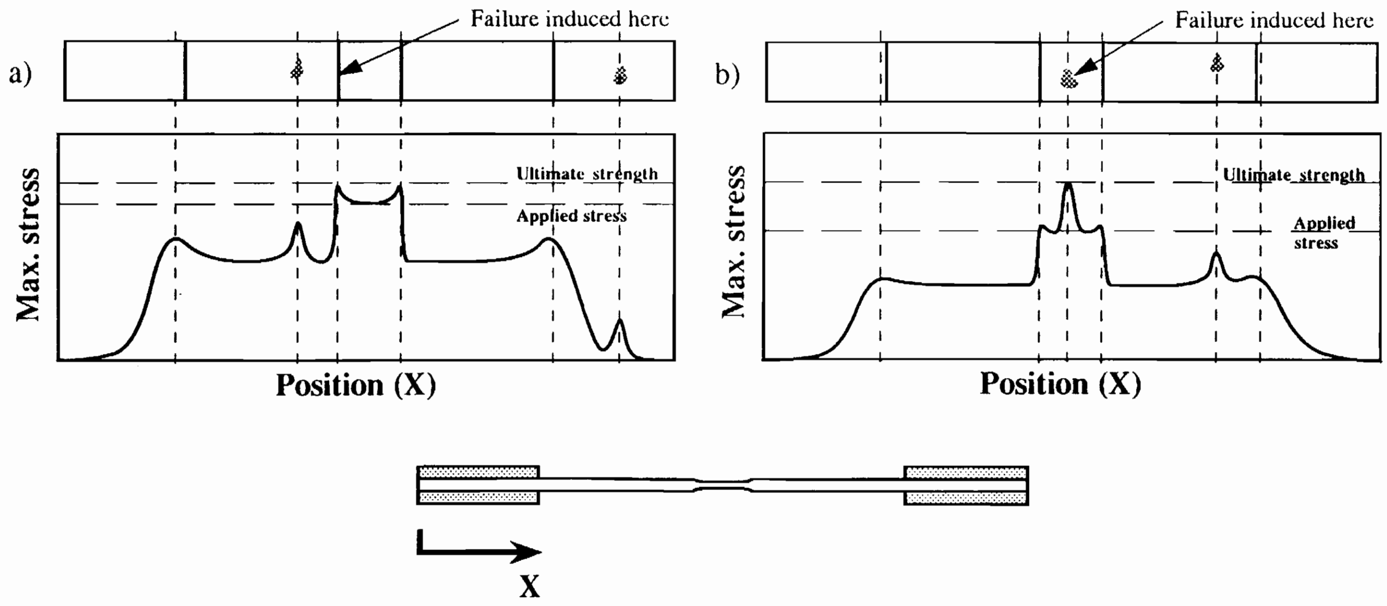


Figure 10. Schematic of maximum axial stresses in CRAG 3.1 coupons containing flaws.

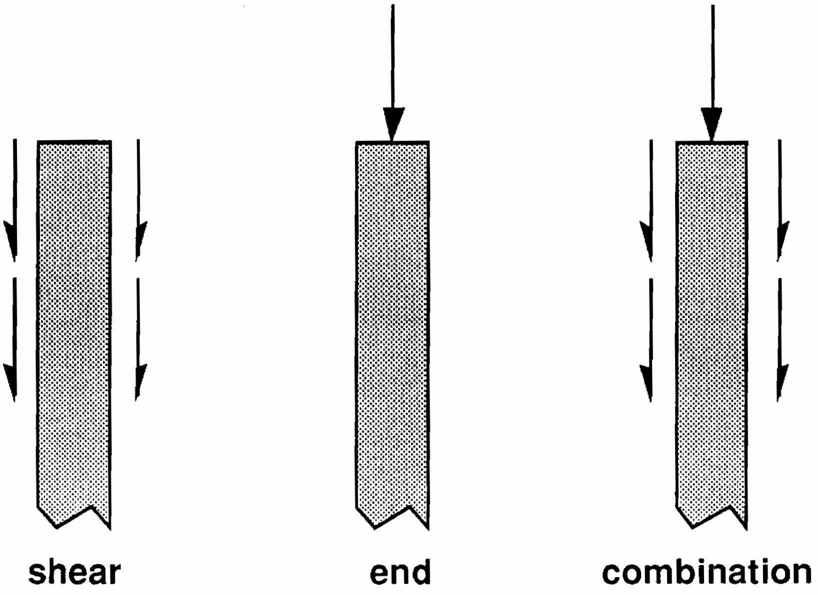


Figure 12. Different compressive loading schemes.

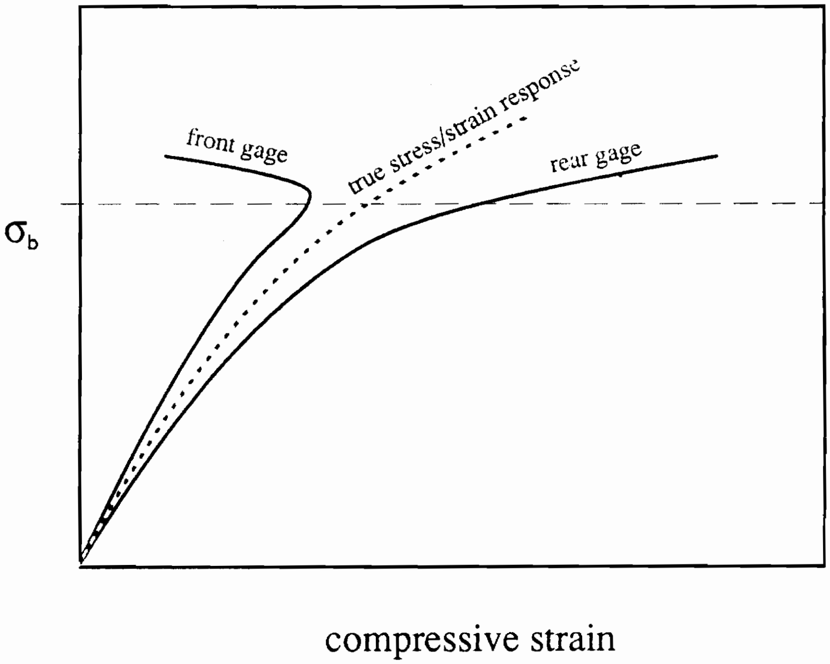


Figure 13. Schematic representation of the stress/strain response of a buckling specimen..

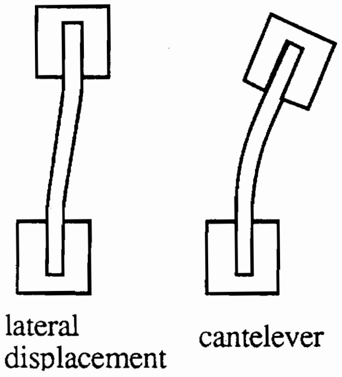
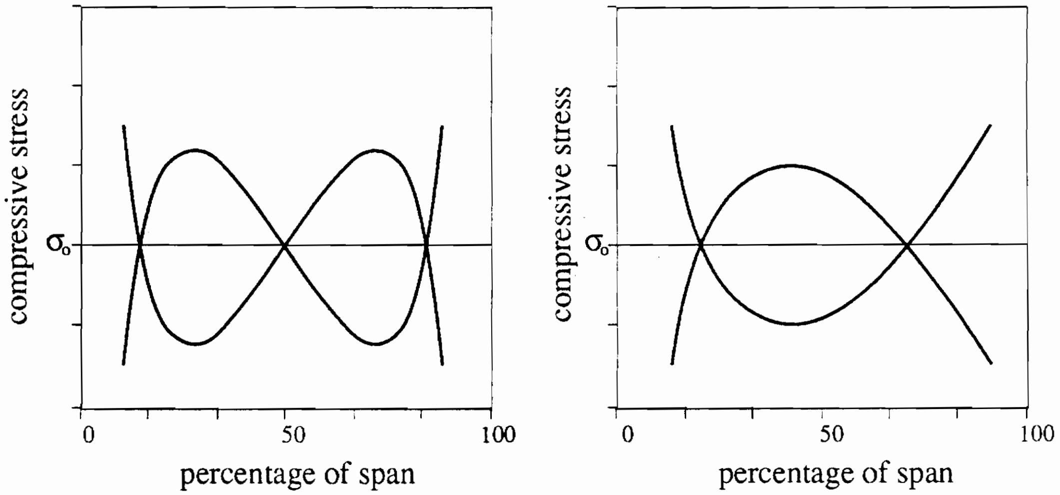


Figure 14. Different types of load eccentricities [28].



(a) (b)

Figure 15. Stress variations from lateral (a) and cantilever (b) displacements (front and back strain gages) [28].

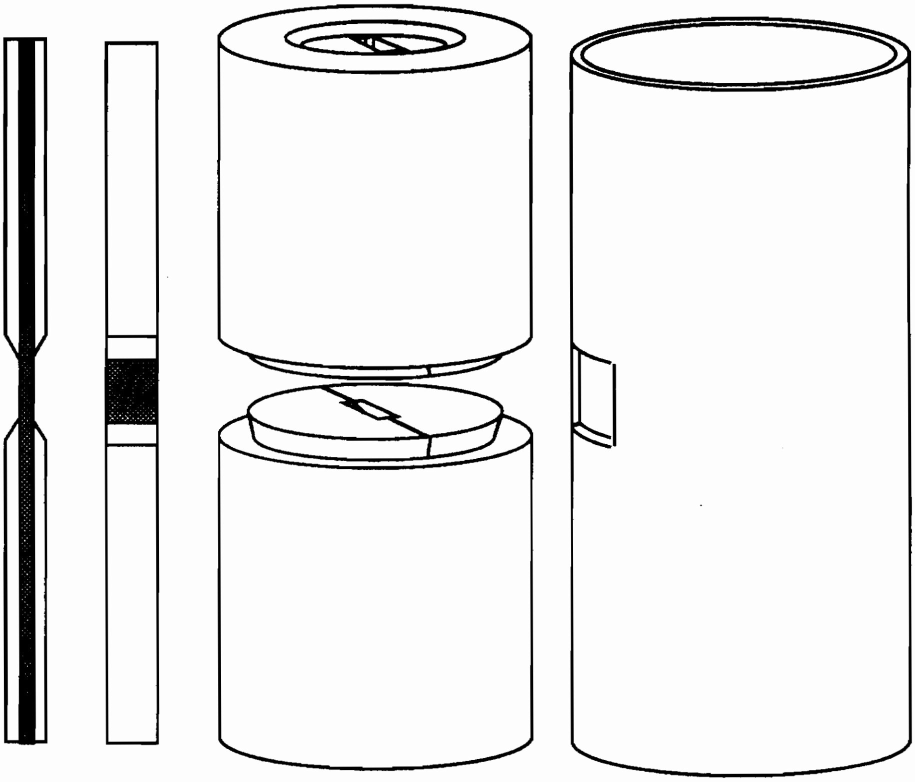


Figure 16. Celanese compression fixture and specimen.

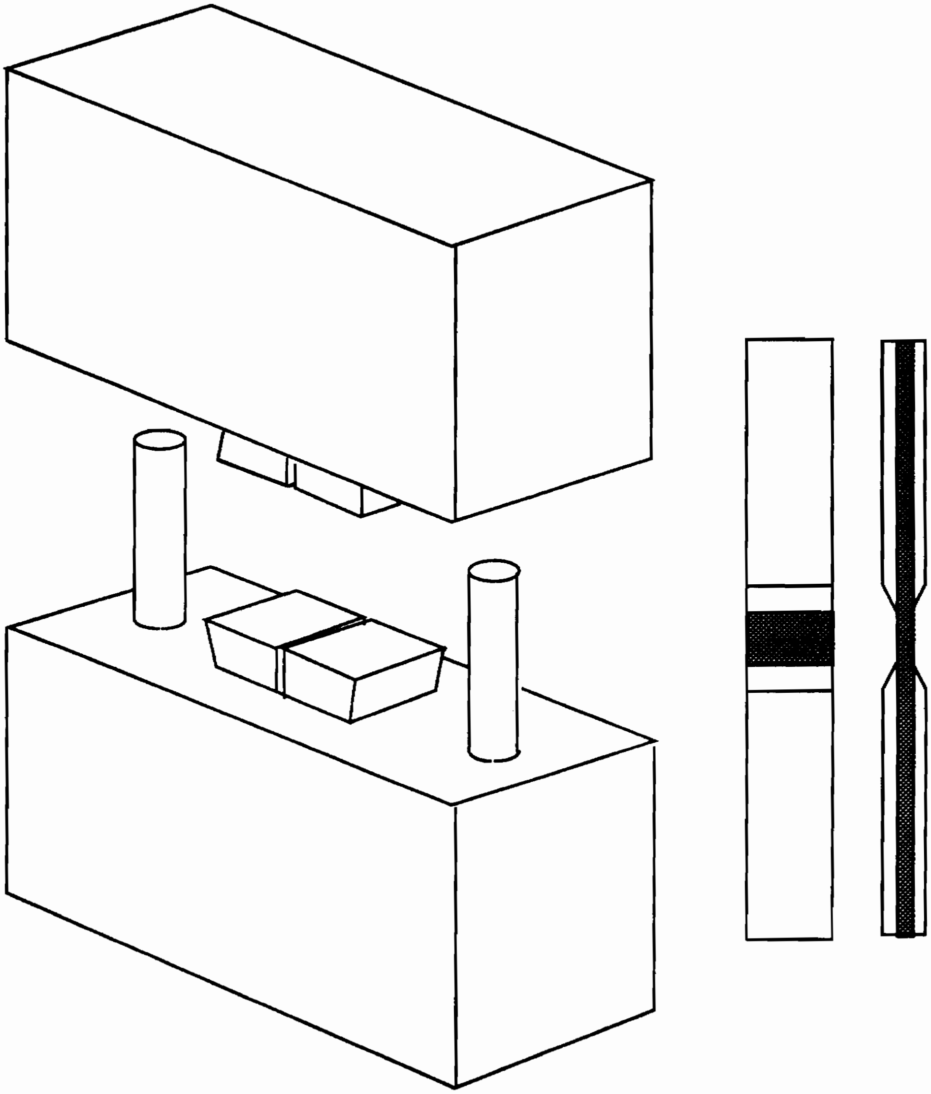


Figure 17. IITRI compression fixture and specimen.

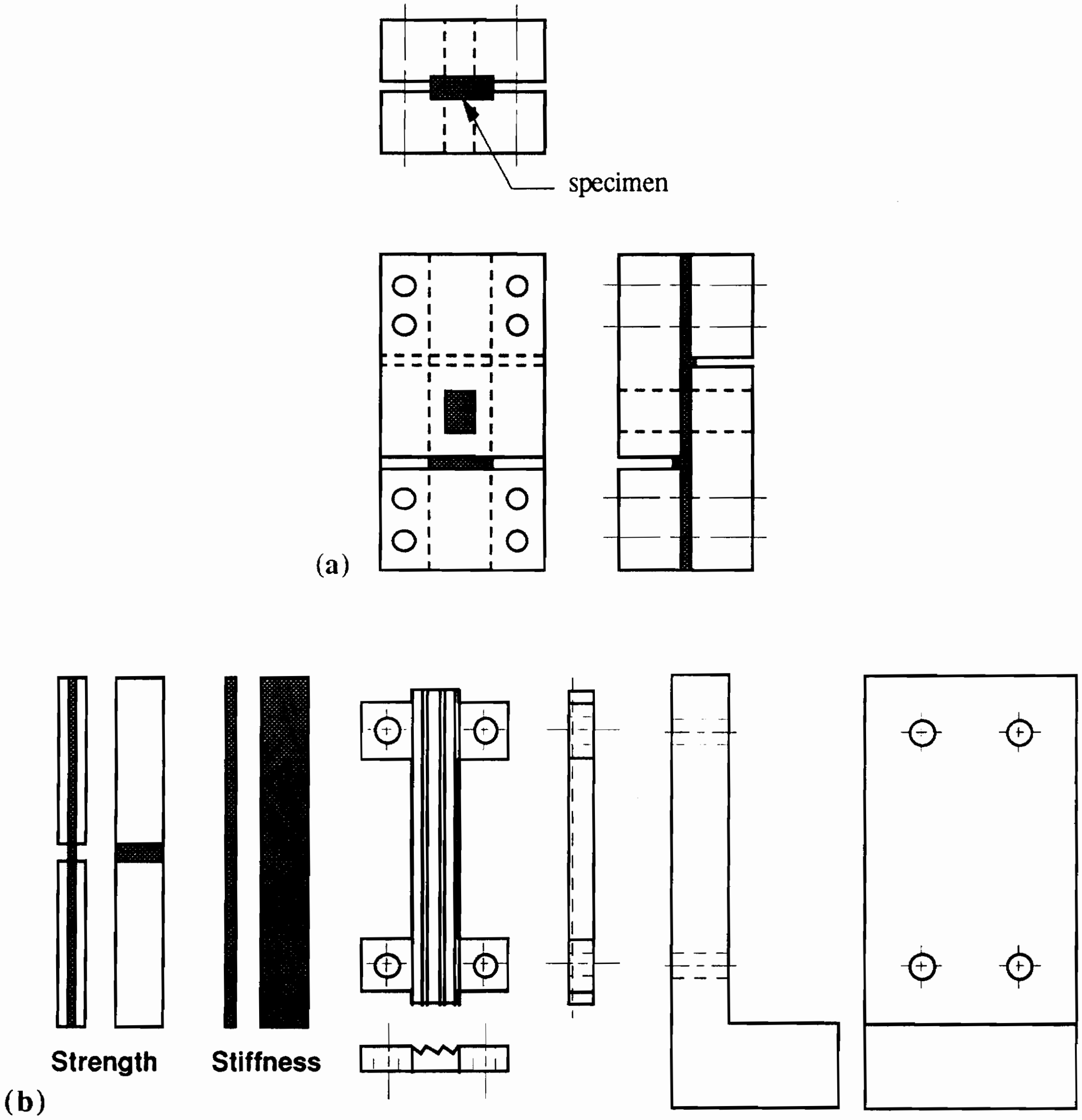


Figure 18. Northrup [29] (a) and SACMA SRM 1 (b) compression fixtures.

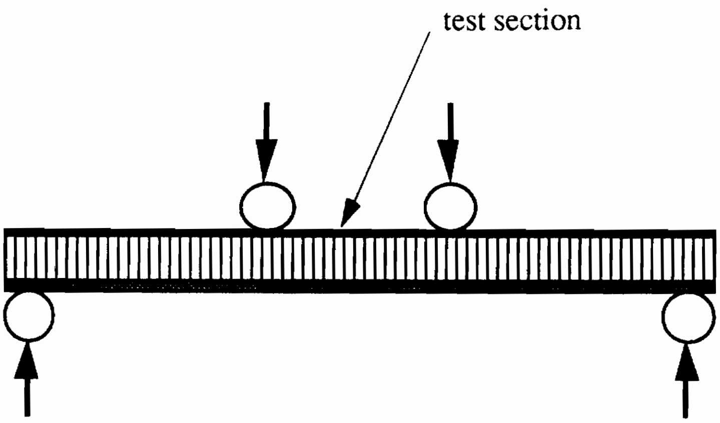


Figure 19. Sandwich beam compressive test.

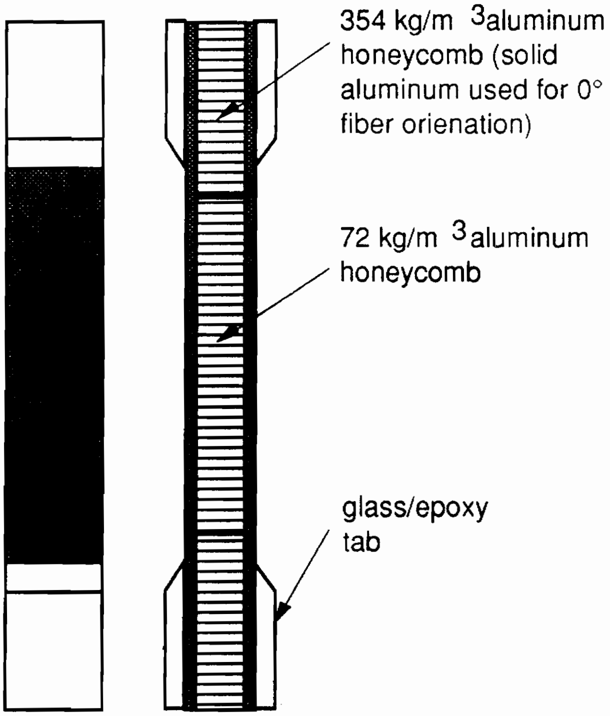


Figure 20. Sandwich column specimen [30].

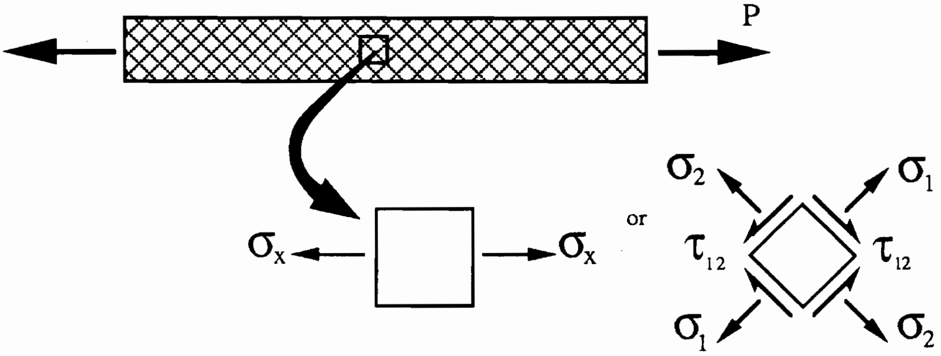


Figure 21. ±45° tensile test for shear stress/strain response.

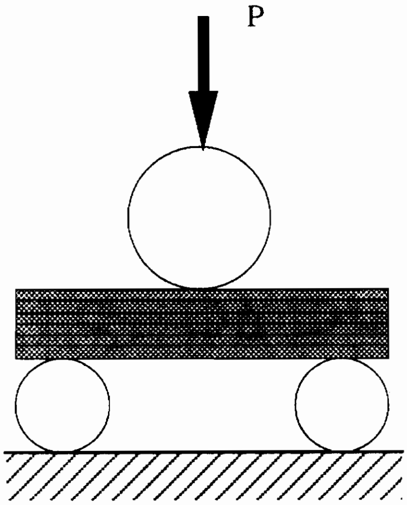


Figure 22. Short beam shear specimen and loading.

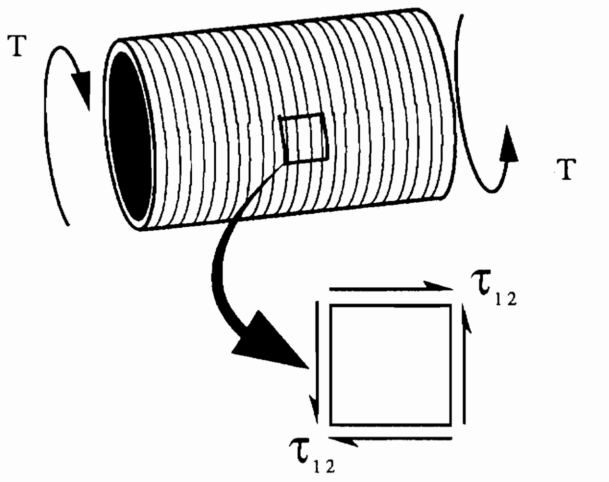


Figure 23. Torsion tube specimen.

Figure 24. Torsion rod specimen.

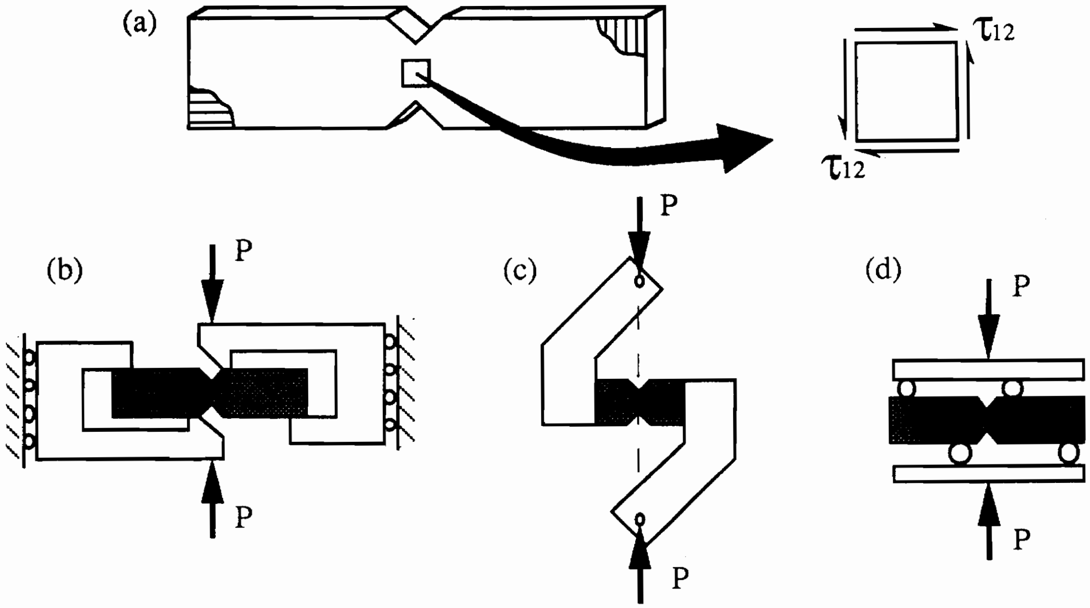


Figure 25. Iosipescu specimen (a) and three loading techniques (b-d).

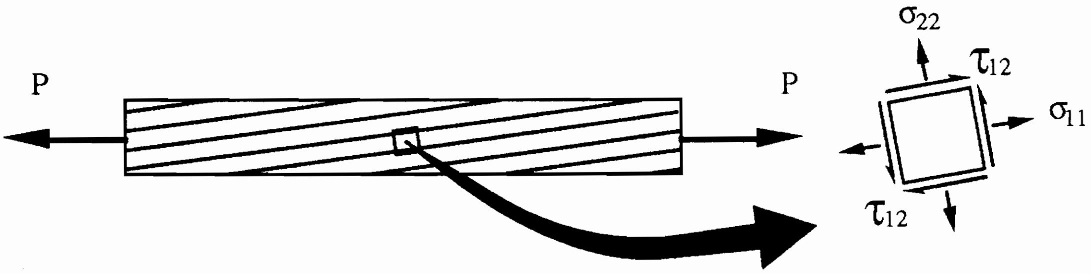


Figure 26. 10° off-axis specimen.

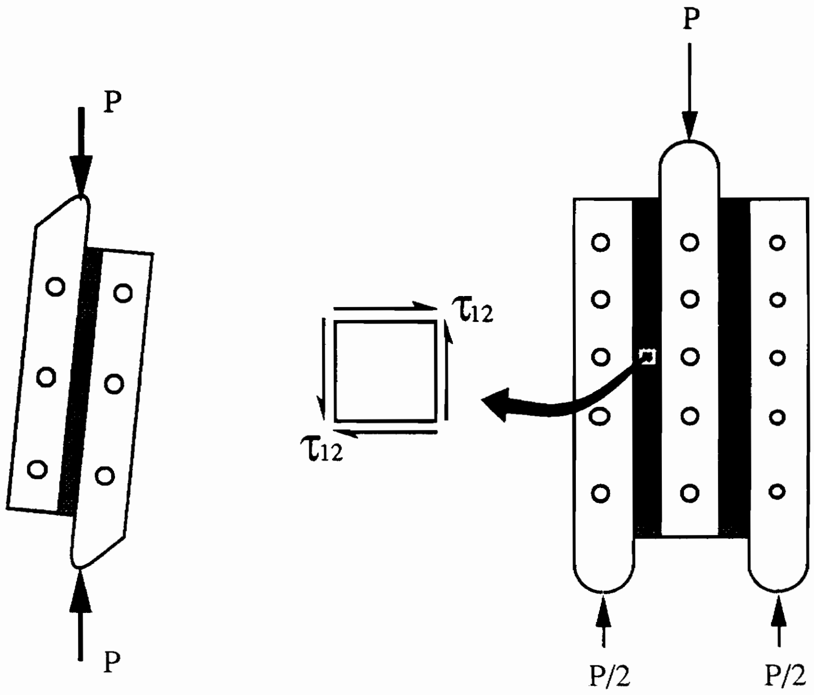


Figure 27. Two- (a) and three-rail (b) shear test.

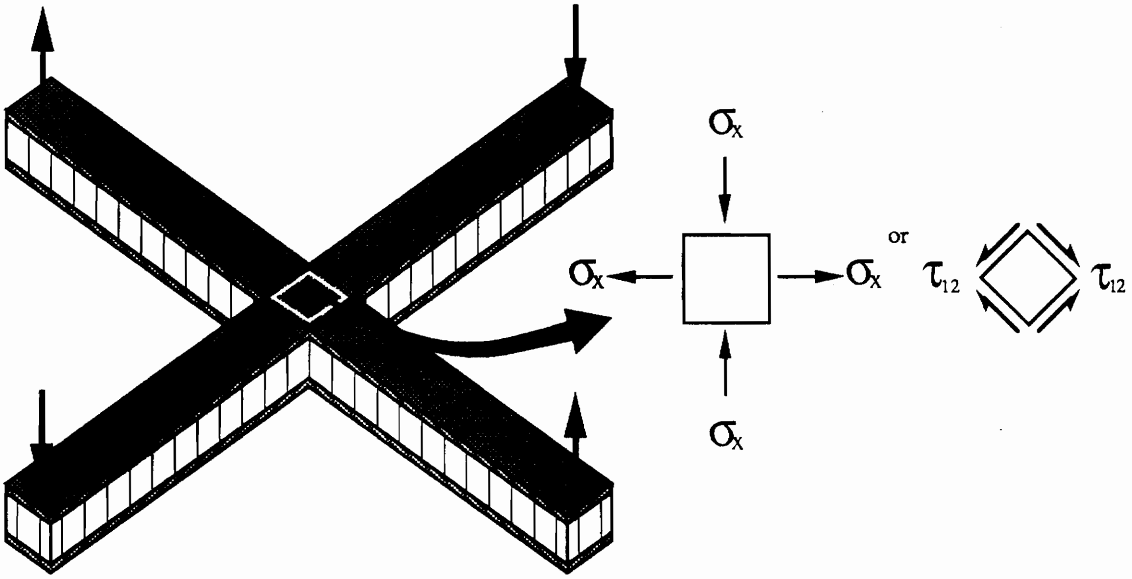


Figure 28. Cross beam test specimen.

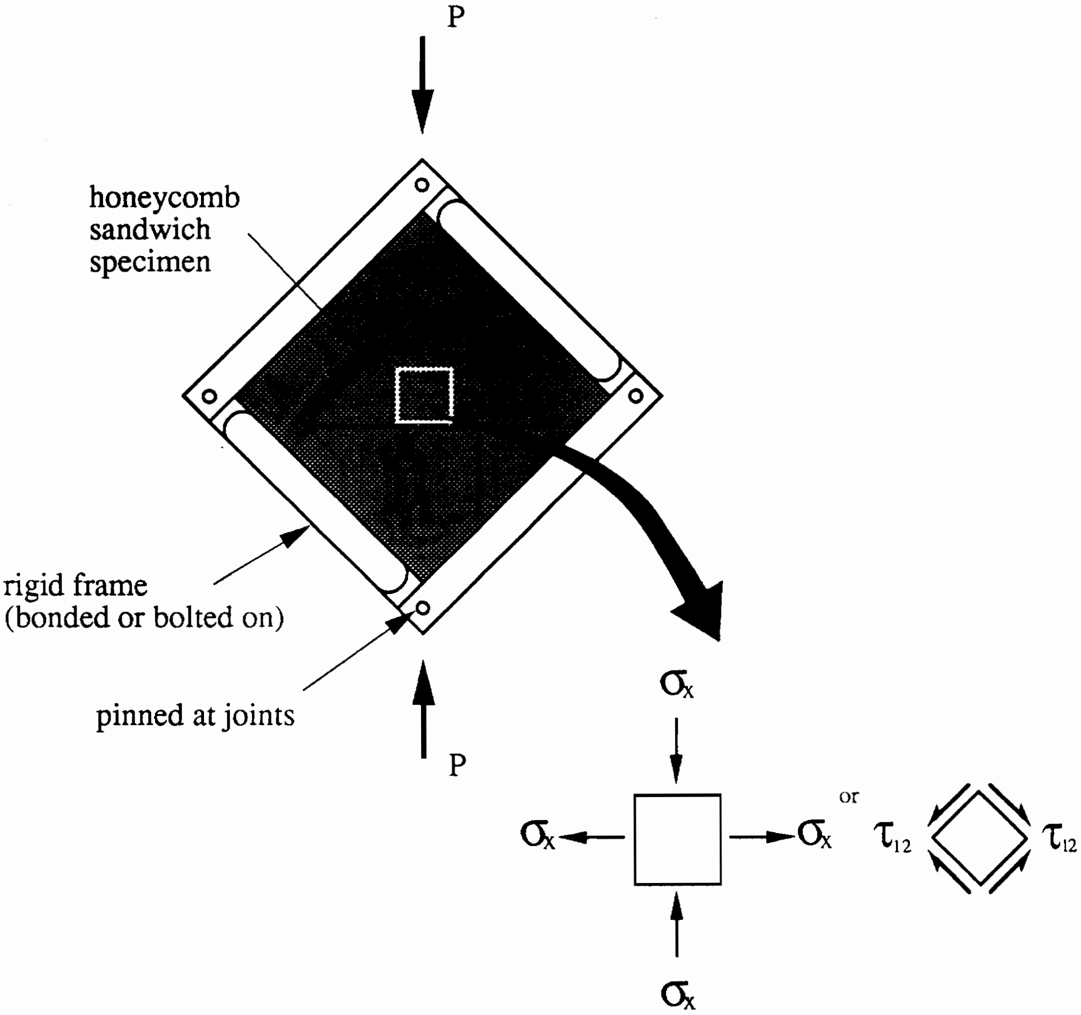


Figure 29. Picture frame assembly.

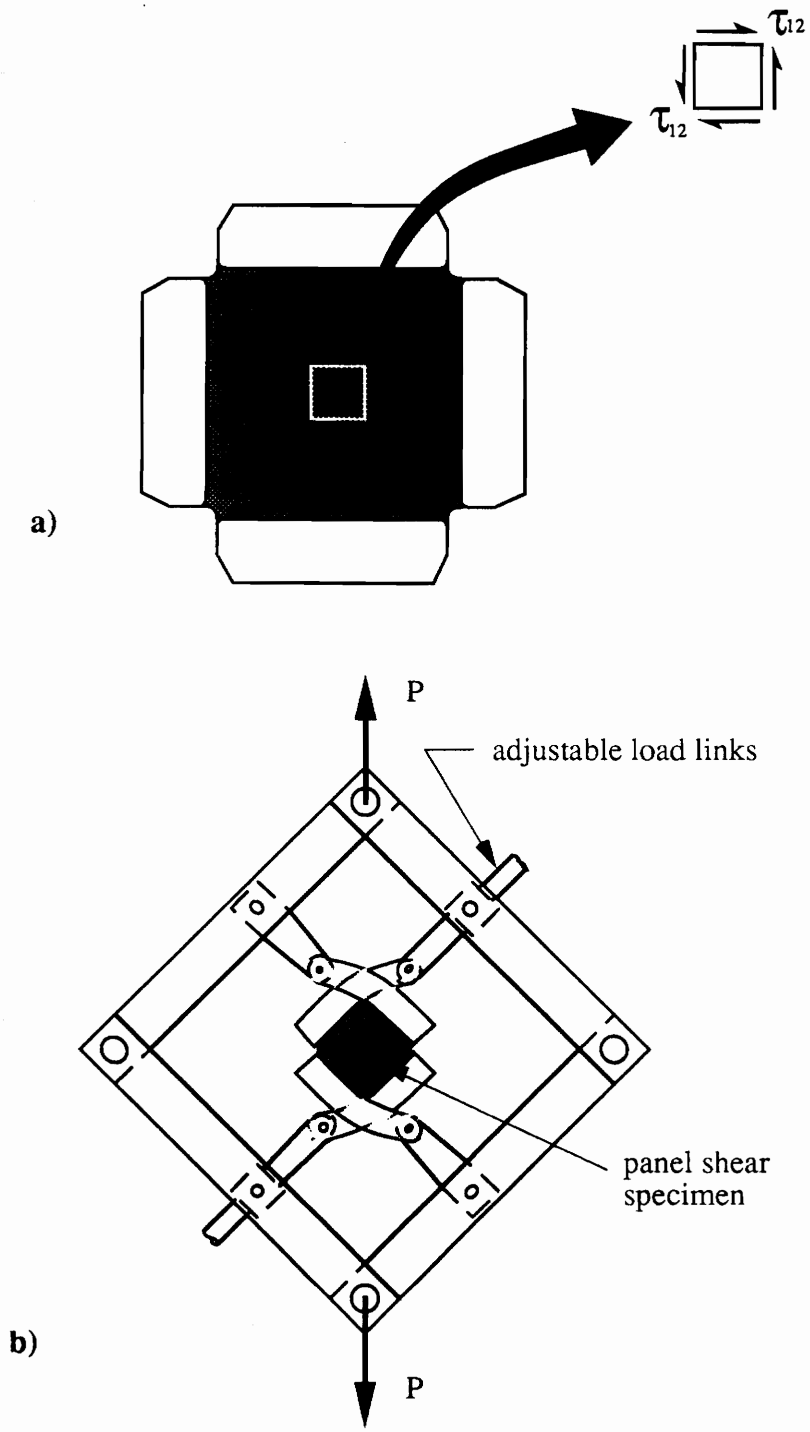


Figure 30. Panel shear specimen (a) and assembly (b).

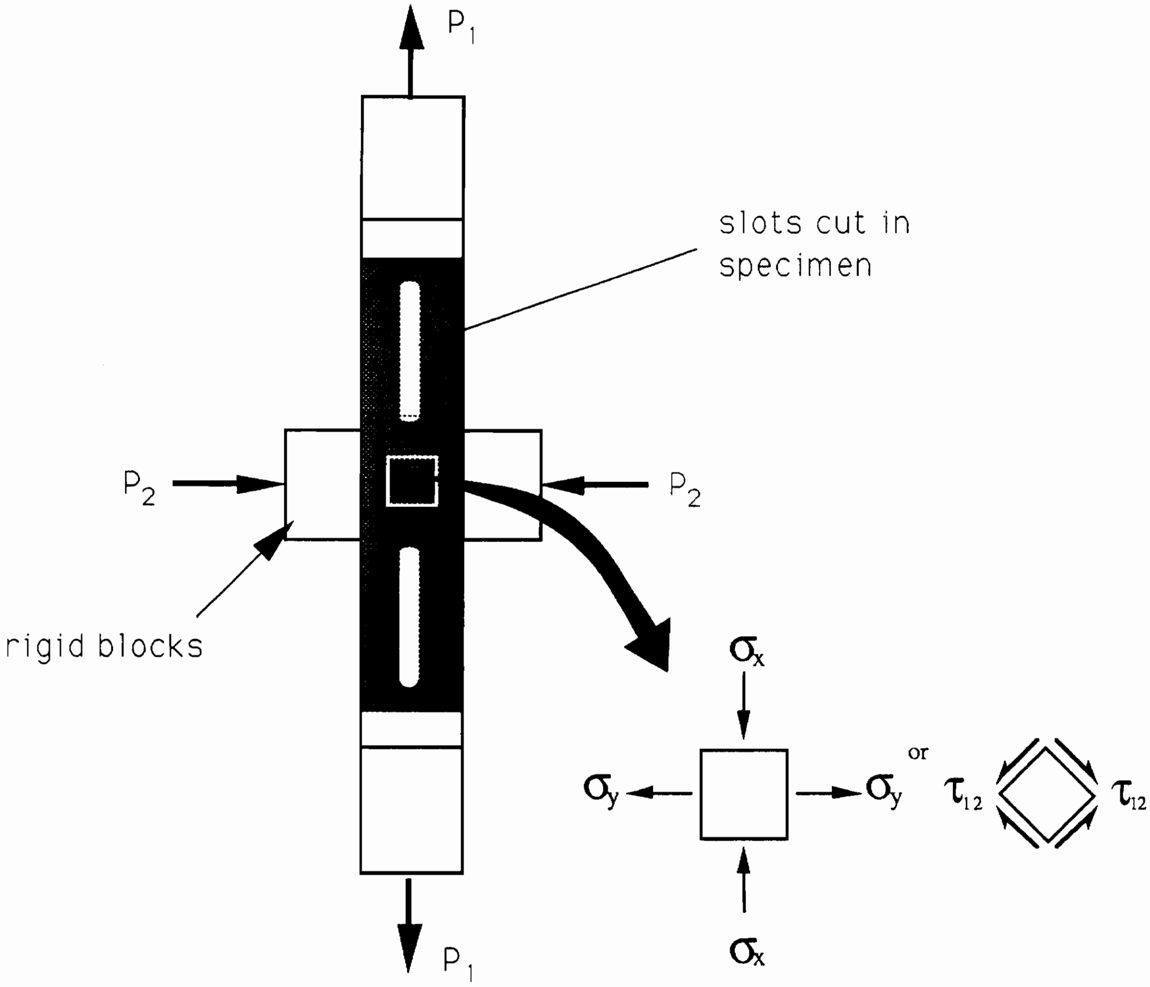


Figure 31. Slotted tensile specimen [57].

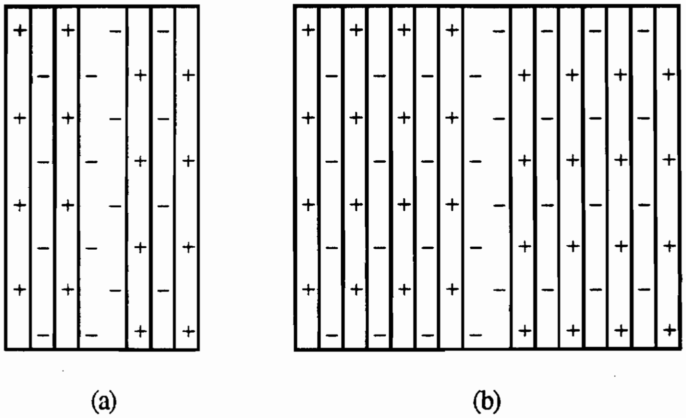


Figure 32. Cross sections of $[\pm45°]_{2S}$ (a) and $[\pm45°]_{4S}$ (b) specimens.

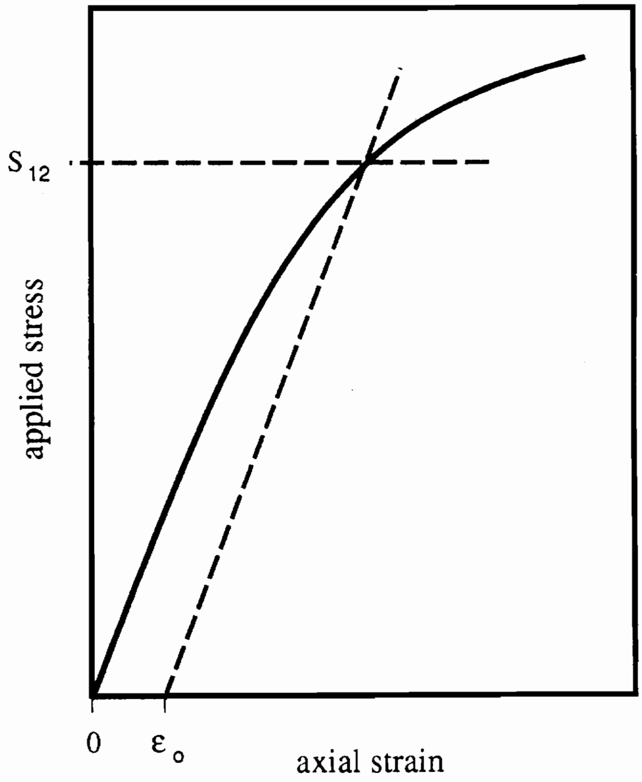


Figure 33. Offset criterion defining shear failure in the ±45° tensile specimen [52].

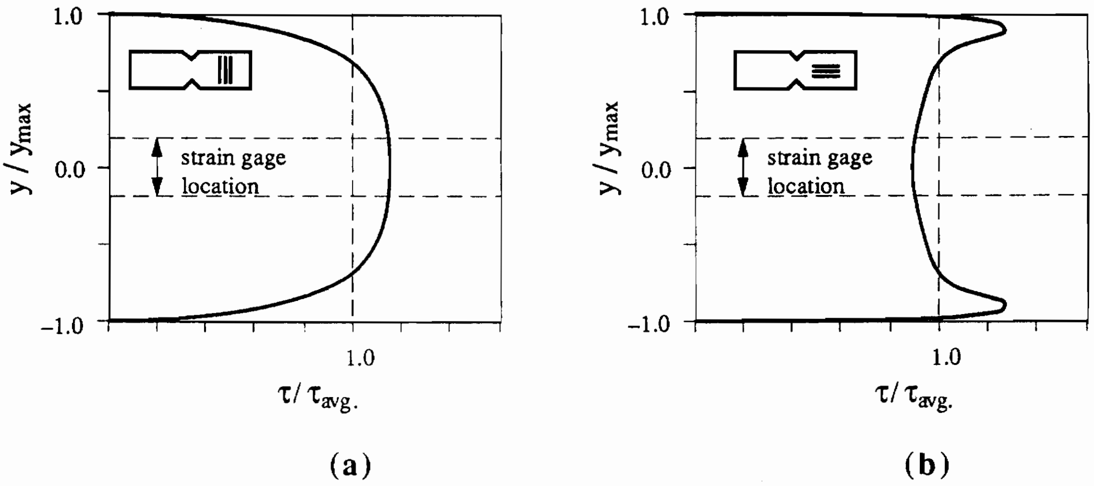


Figure 34. Shear stress distribution through notch depth in 90° (a) and 0° (b) Iosipescu specimens [43].

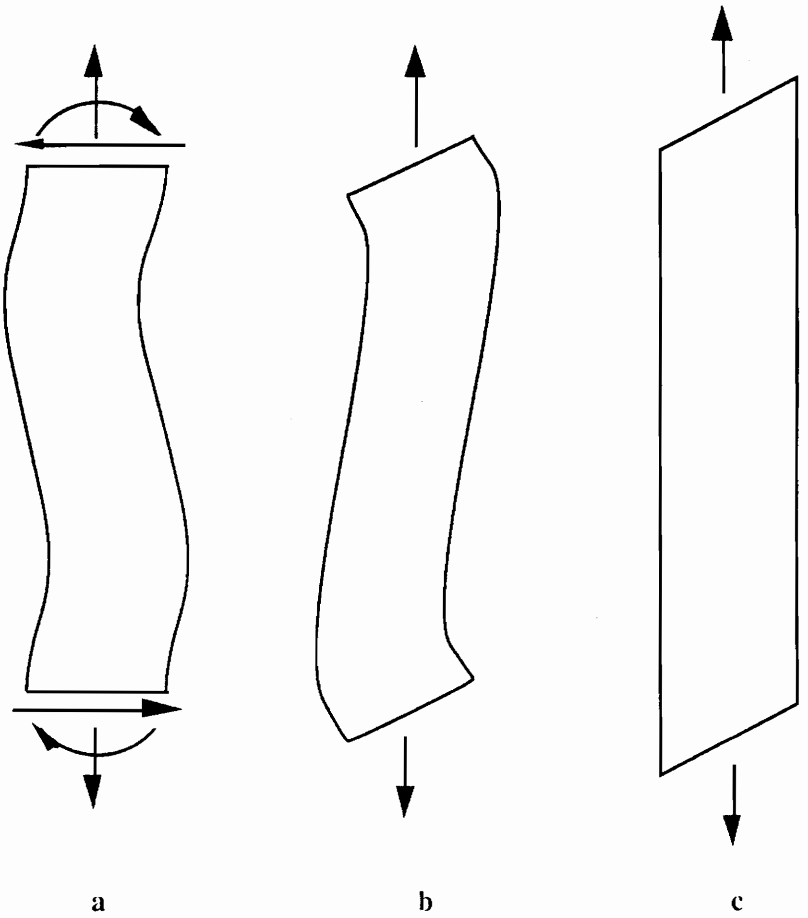


Figure 36. Off-axis composite coupon deformations; clamped (a), NASA fixture [55] (b) and free edge (c).

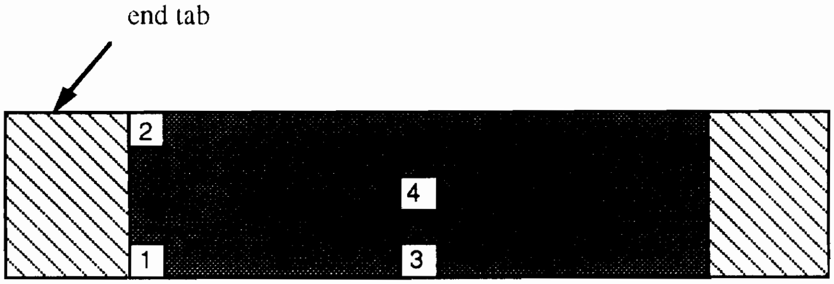


Figure 35. Location of strain gages used by Sun and Berreth [56].

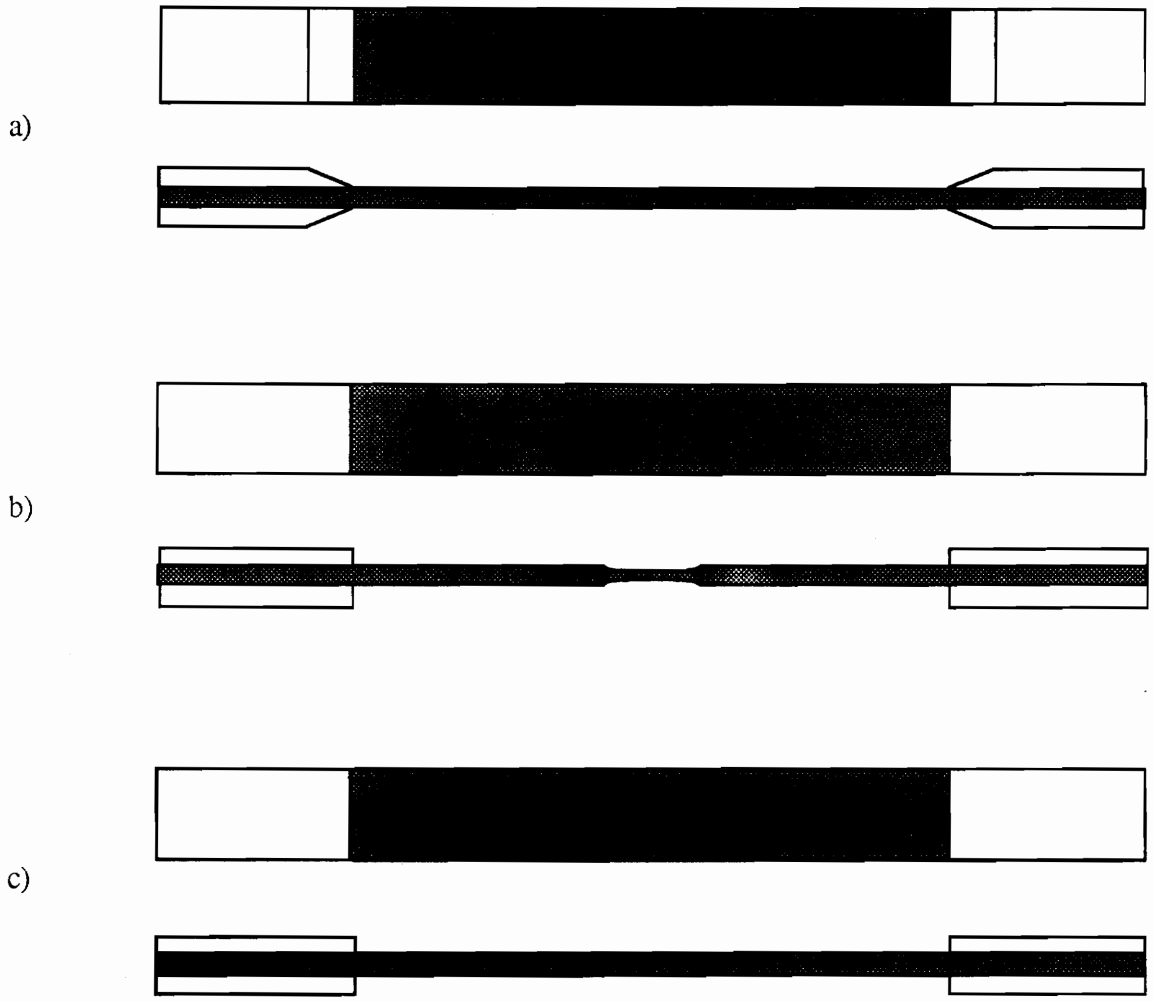


Figure 37. ASTM D 3039 or SACMA SRM 4 (a), CRAG 3.1 (b) and CRAG 3.2 specimens.

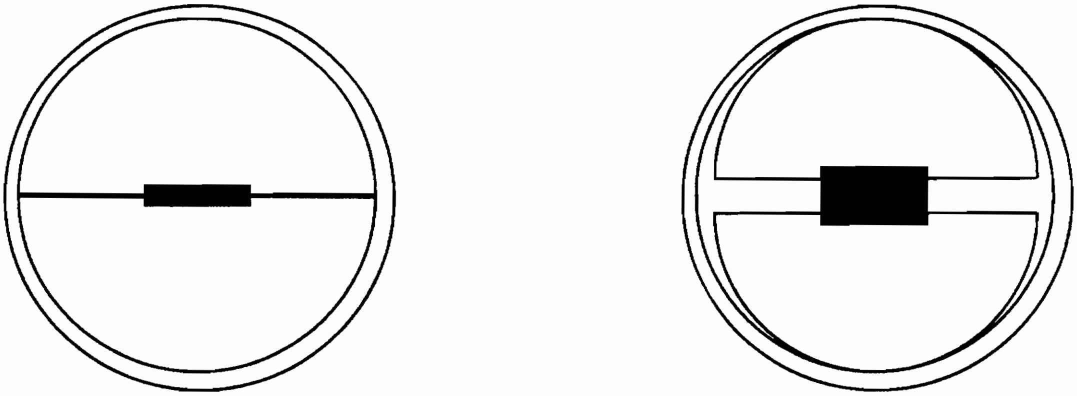


Figure 38. Effect of specimen width on conical grips [27].

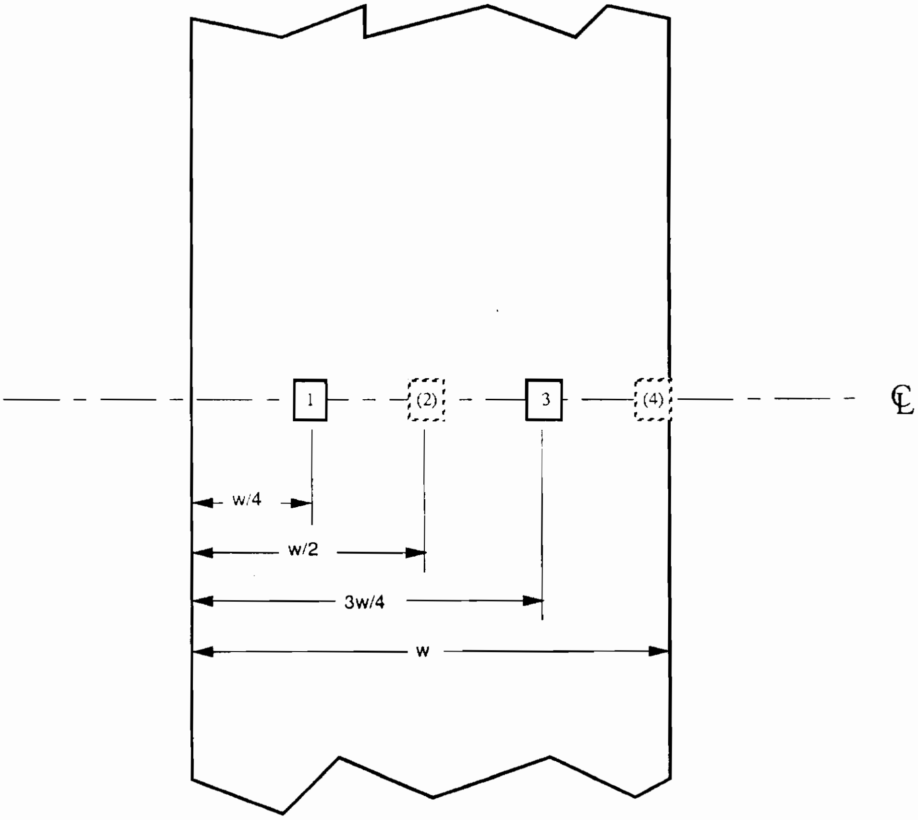


Figure 39. Location of strain gages on specimen [24]

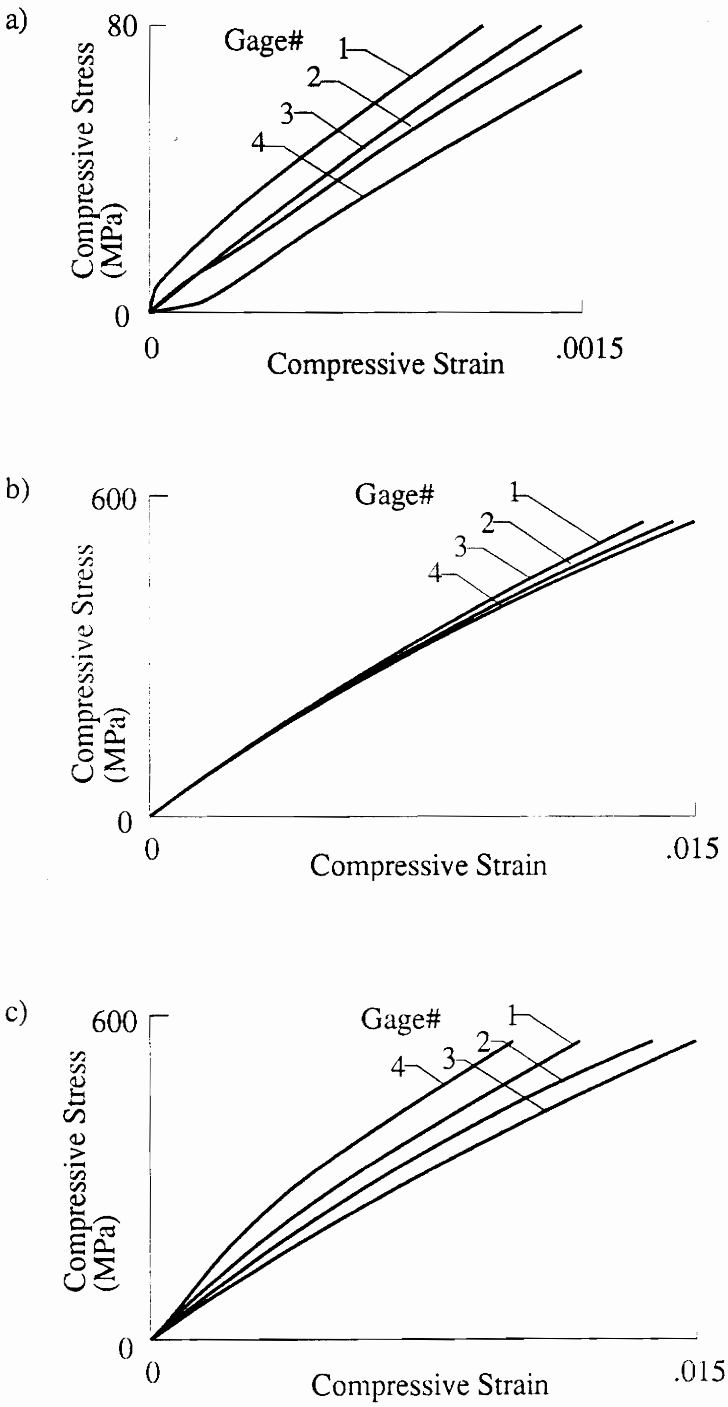


Figure 40. Stress/strain curves for quasi-isotropic specimen, unground (a), typical specimen (b) and worst case specimen (c) [24].

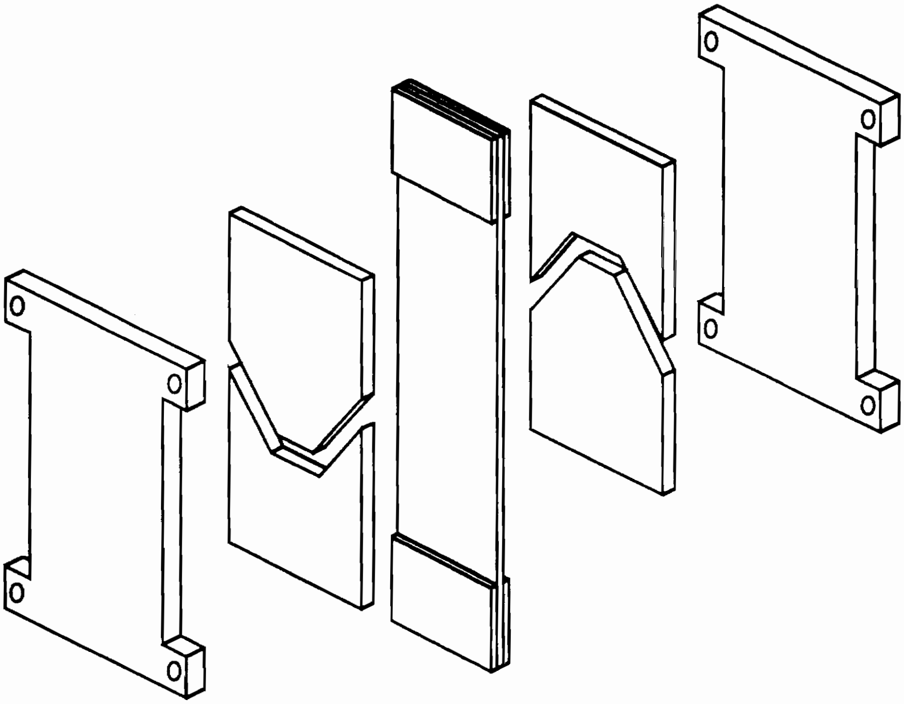


Figure 41. Face supported fixture and specimen [28].

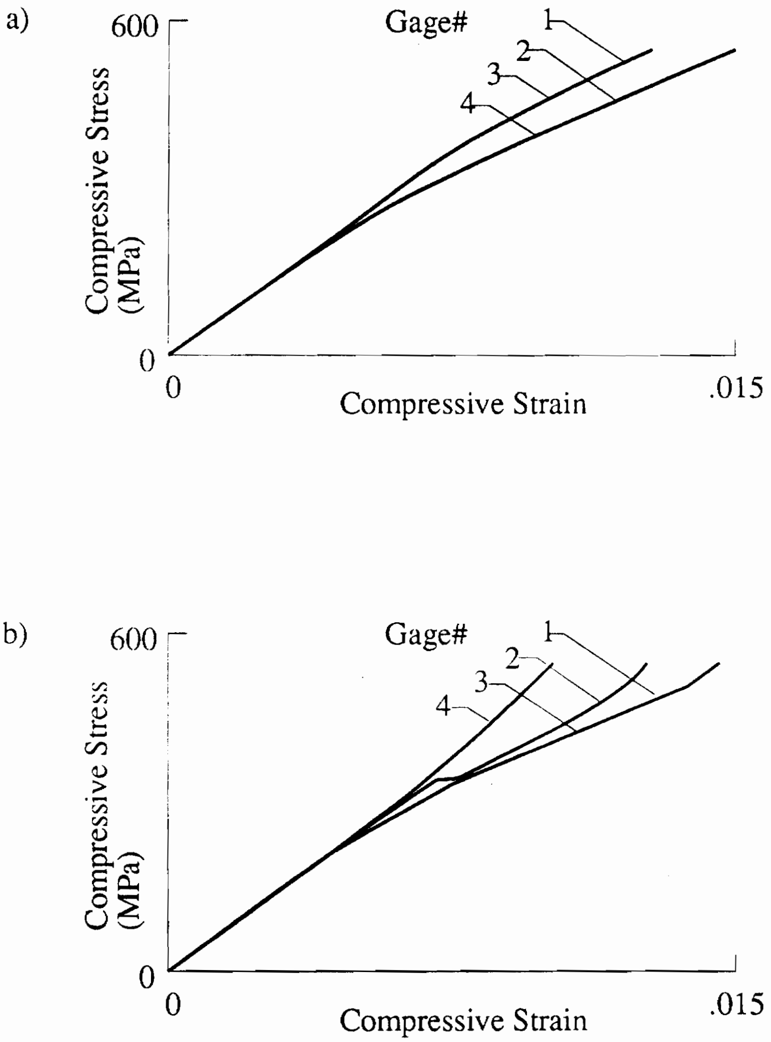


Figure 42. Typical (a) and worst case (b) stress/strain curves for quasi-isotropic face supported specimen [24].

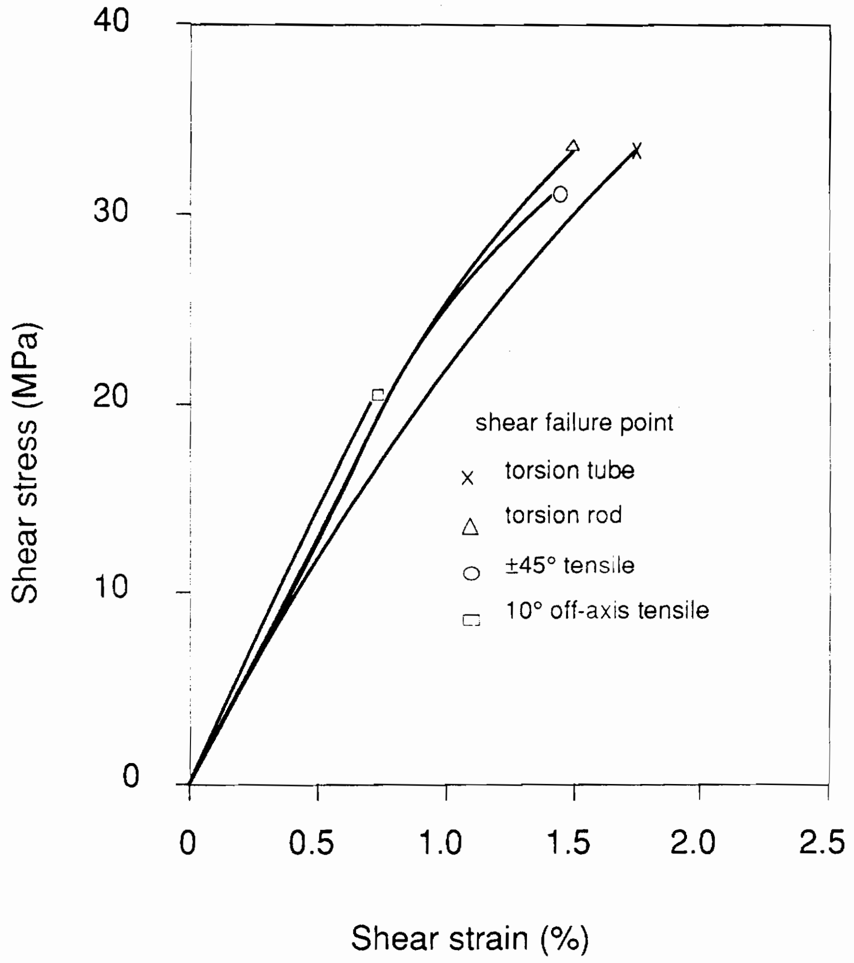


Figure 43. Stress/strain behavior measured by different techniques [52].

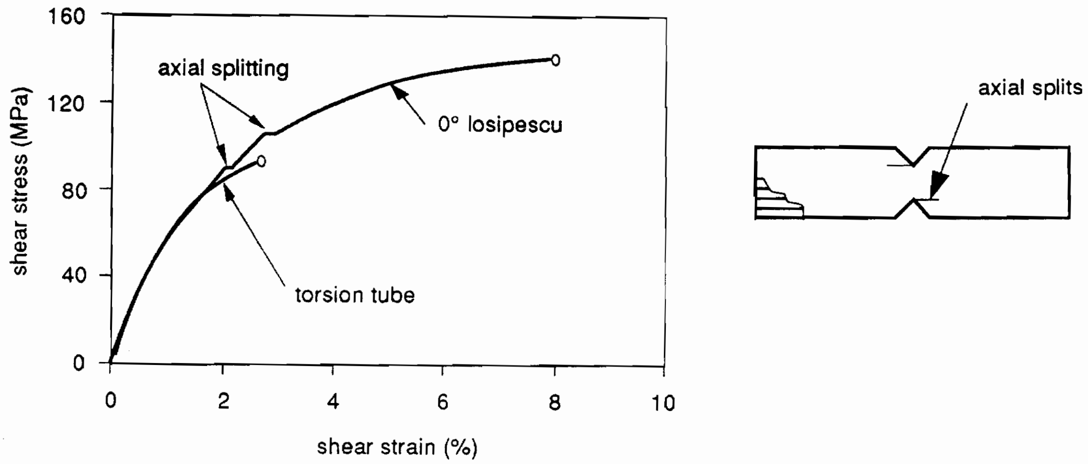


Figure 44. Stress/strain results from the torsion tube and Iosipescu tests [52].

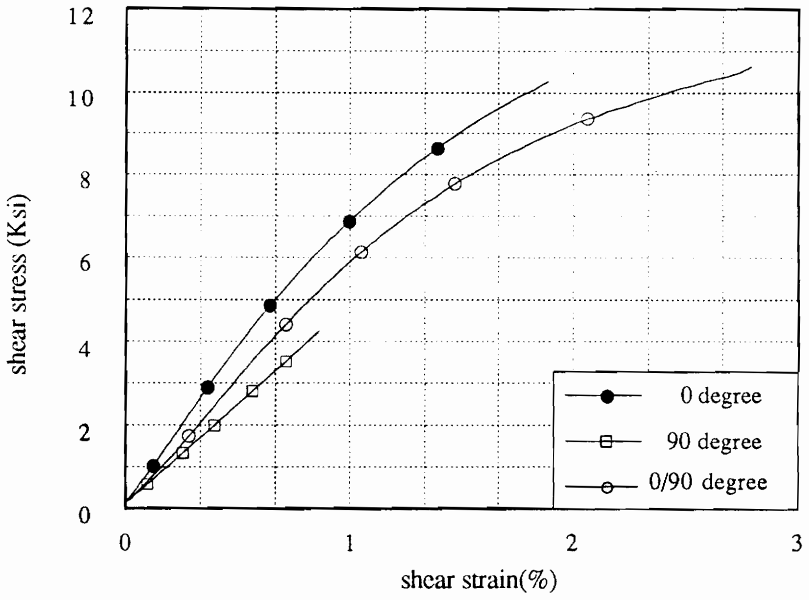


Figure 45. Stress/strain results for 0°, 90° and 0°/90° Iosipescu specimens [43].

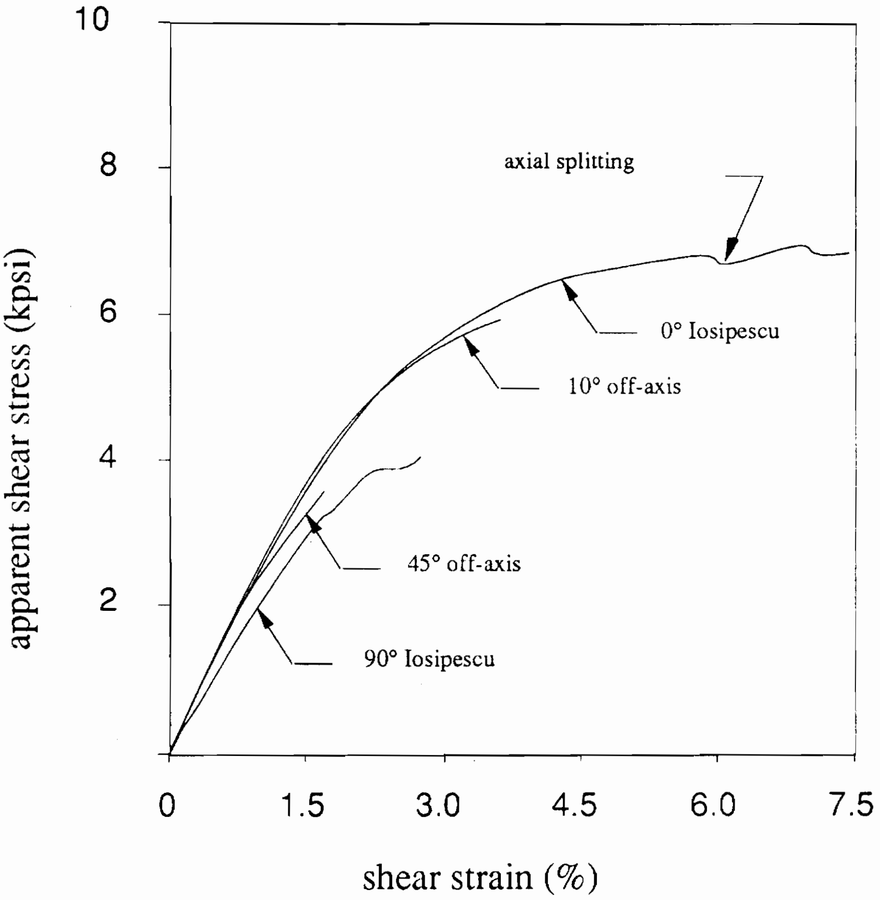
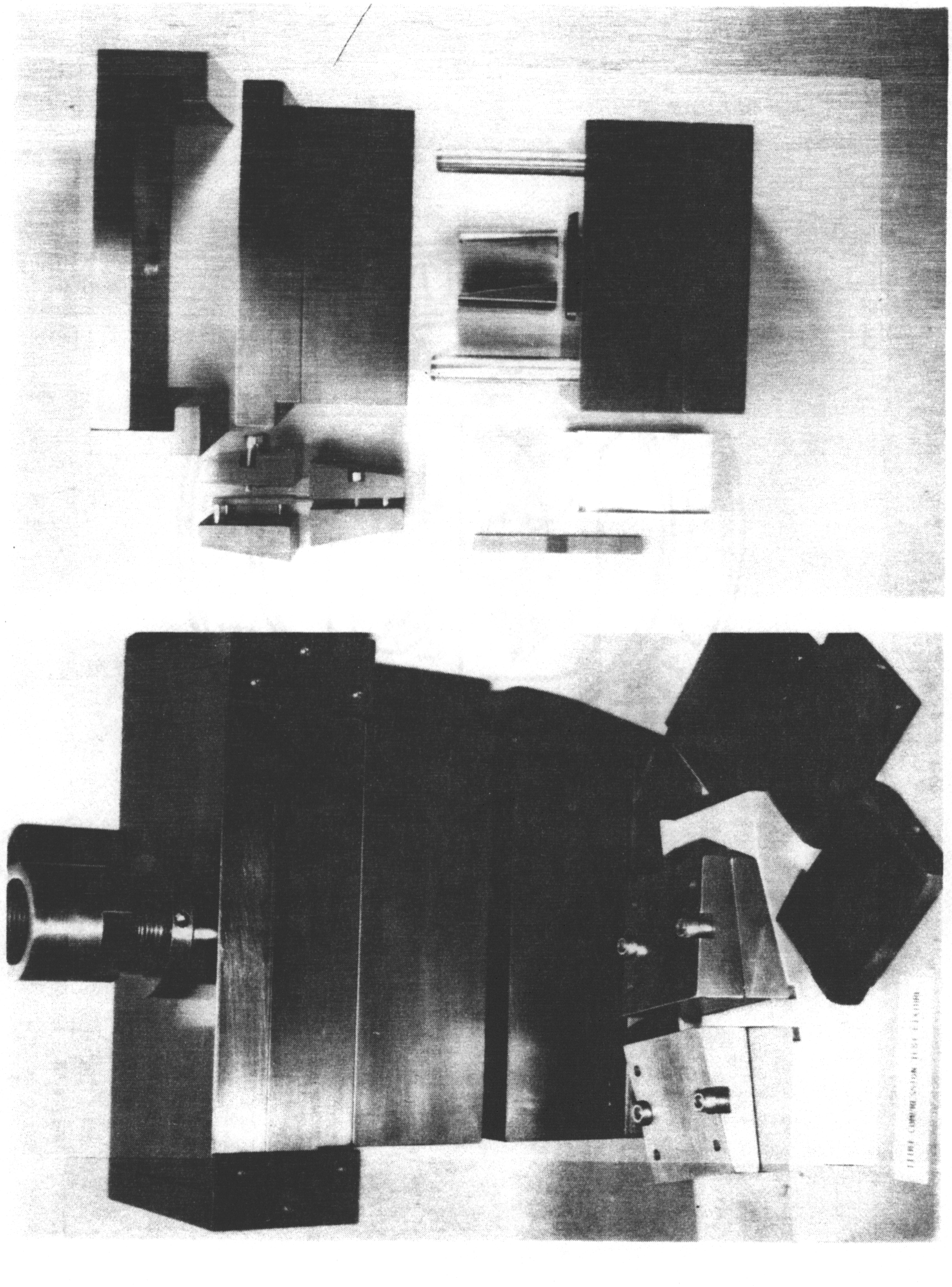


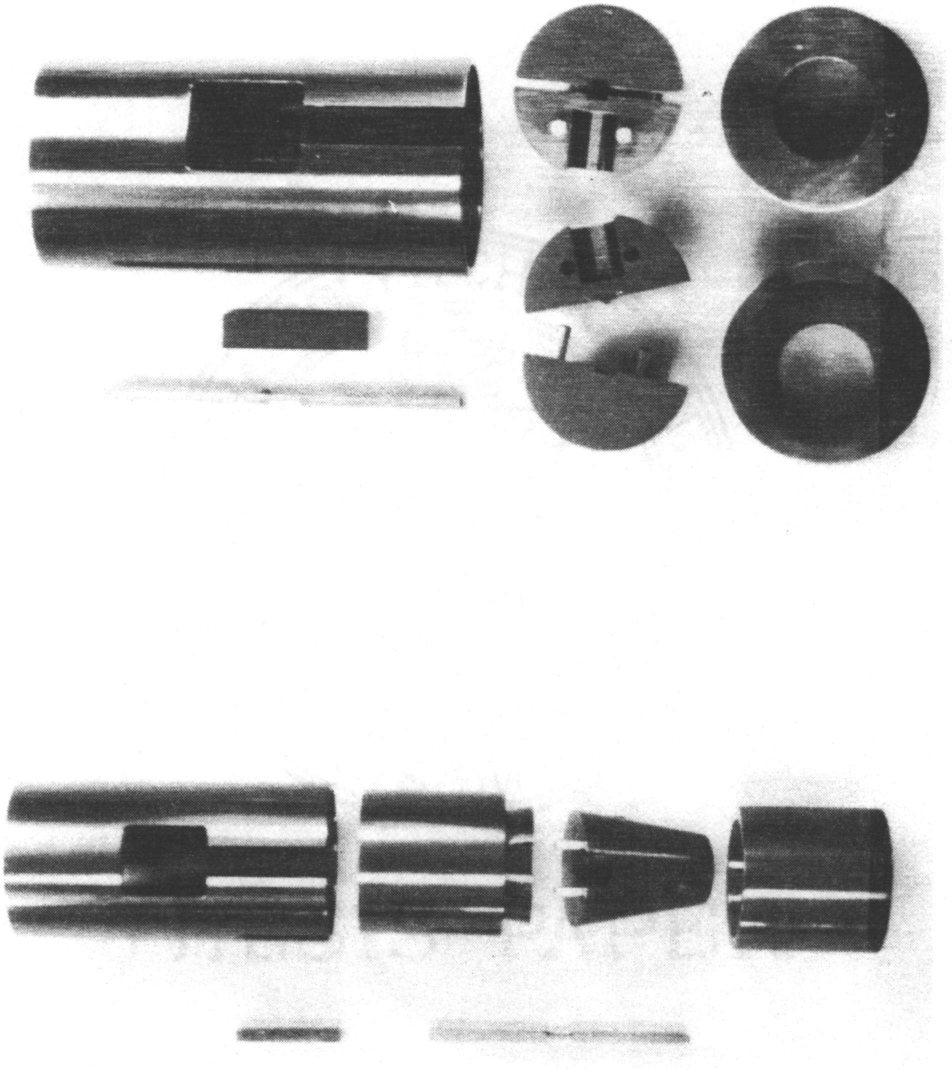
Figure 46. Stress/strain results from several test methods [54].

APPENDIX

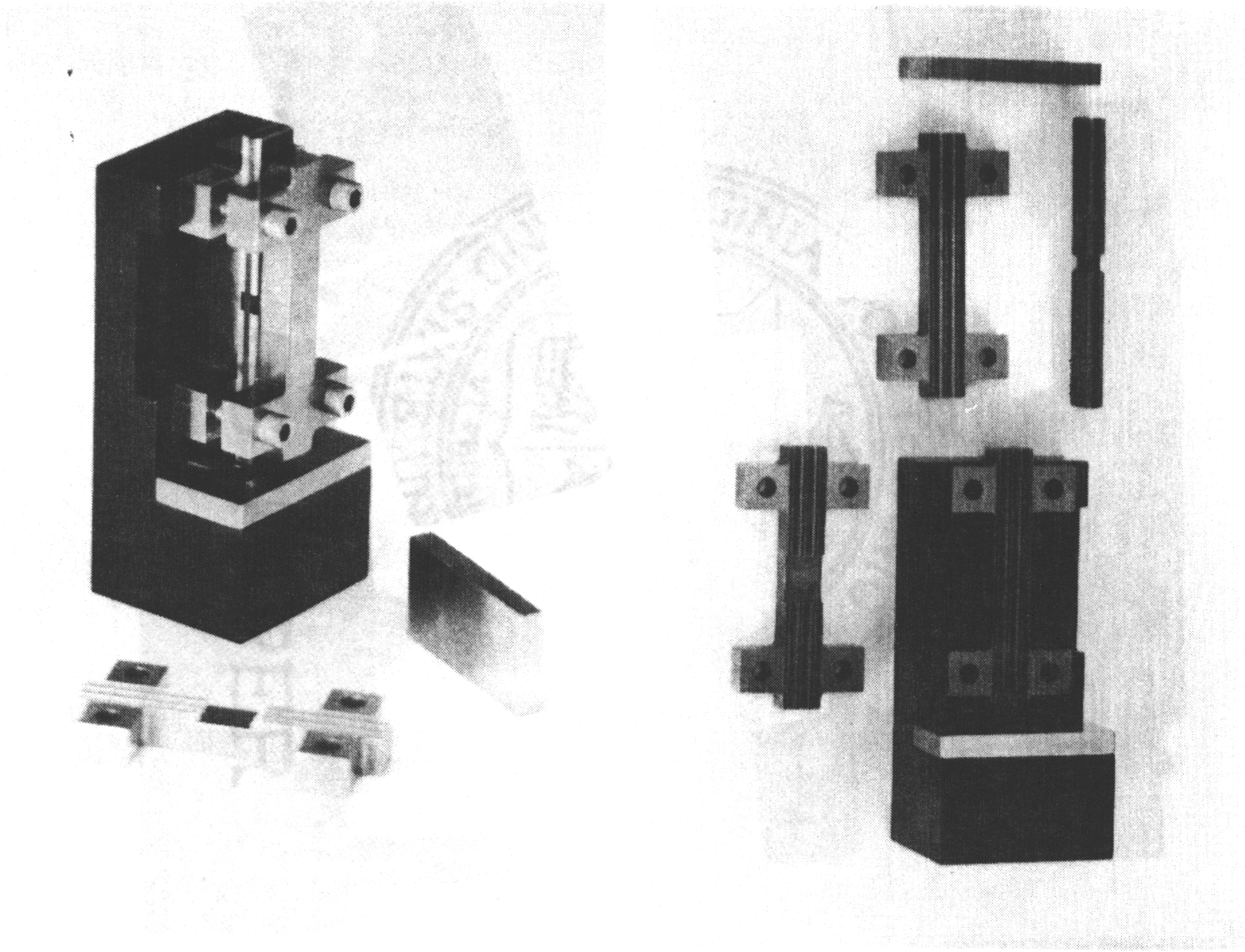
Selected test fixtures.



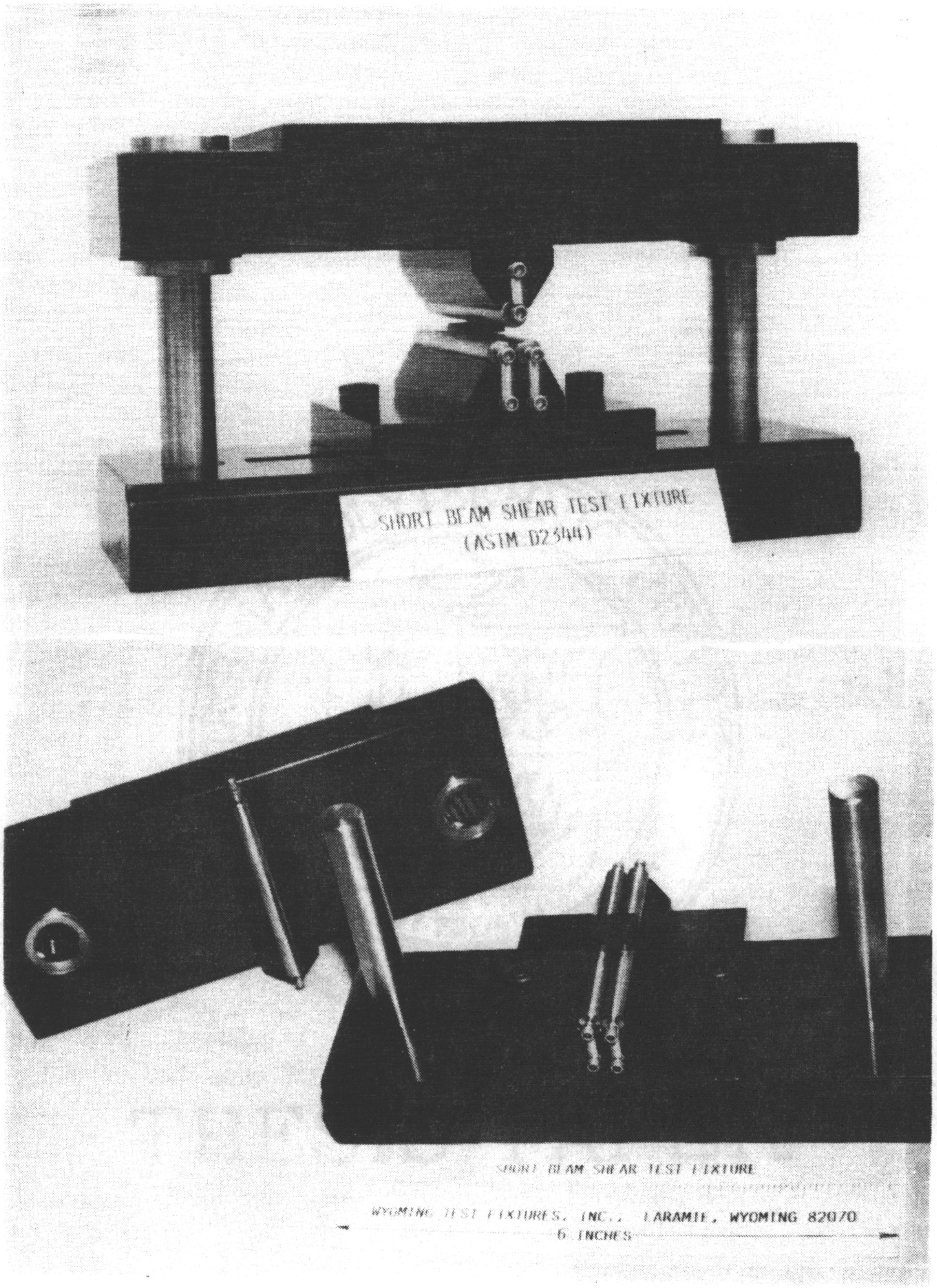
IITRI Compression Fixture.



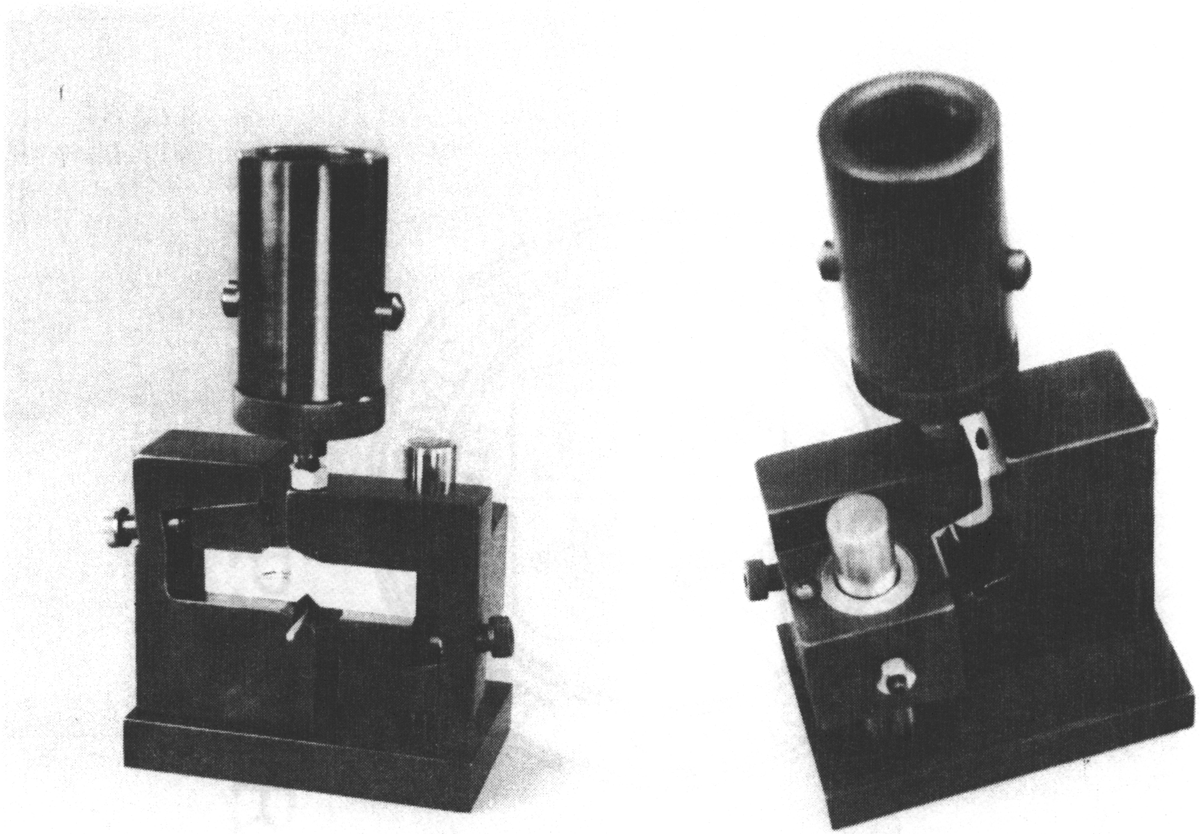
Celanese Compression Fixture.



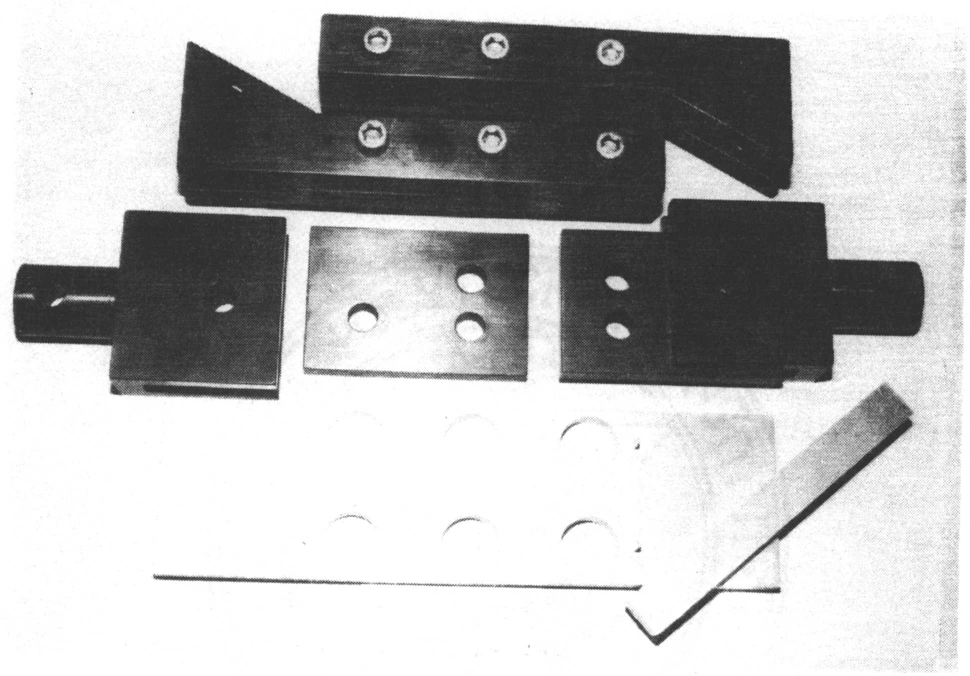
Modified ASTM D 695 Fixture.



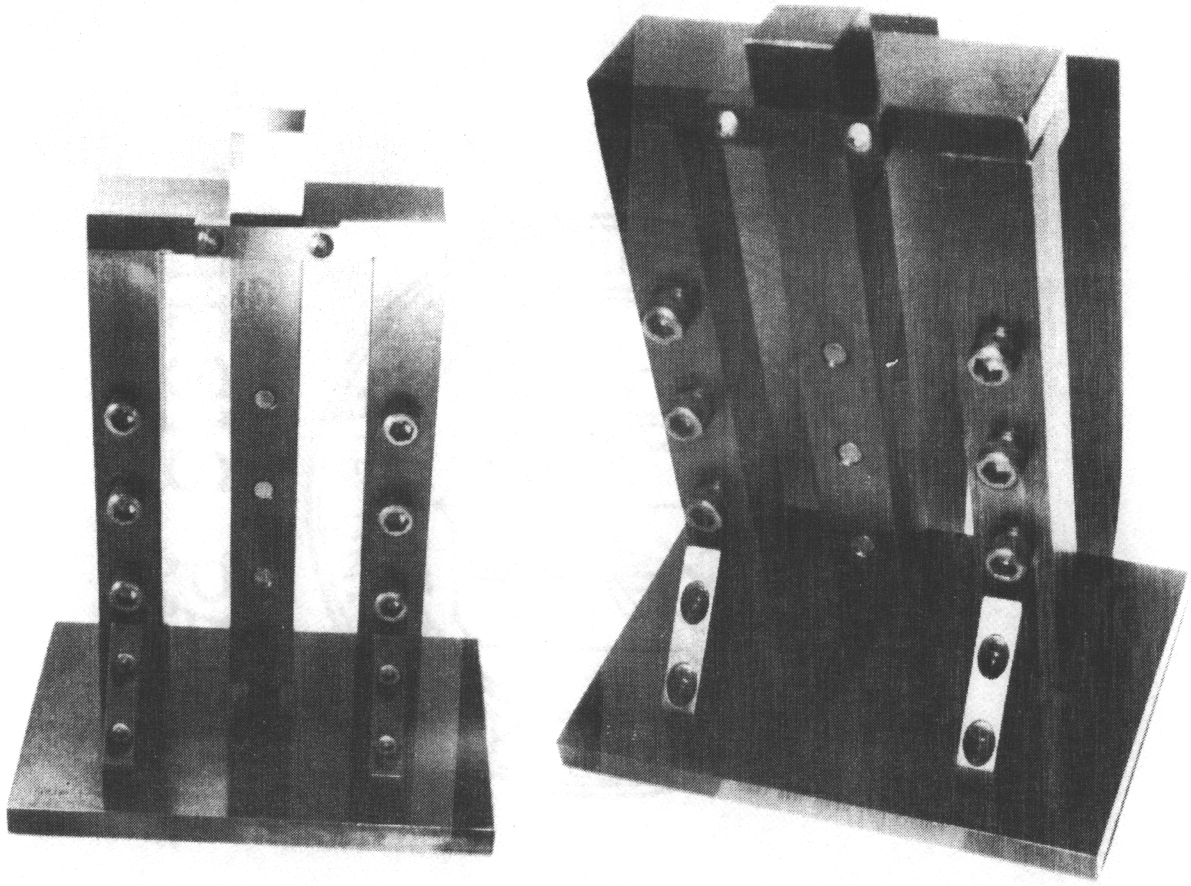
Short Beam Shear Fixture.



Iosipescu Shear Fixture.



Two Rail Shear Fixture.



Three Rail Shear Fixture.

VITA

David Page Johnson was born June 18, 1963 in Evanston, Illinois. After graduating from New Trier East High School in Winnetka, Illinois, he attended Brigham Young University in Provo, Utah. In April 1989 he received a Bachelor of Science degree in mechanical engineering. In August 1989, he entered graduate studies at Virginia Polytechnic Institute and State University pursuing a Masters of Science degree.

David P. Johnson