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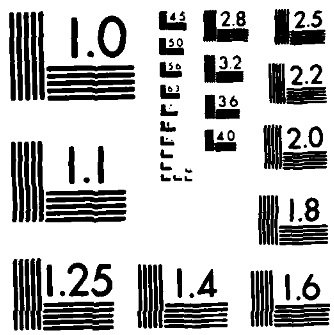

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IN-PLANE SHEAR PROPERTIES OF GRAPHITE FIBRE/EPOXY COMPOSITES FOR AEROSPACE APPLICATIONS:

EVALUATION OF TEST METHODS BY THE DECISION ANALYSIS TECHNIQUE

by

S. Lee, M. Munro

National Aeronautical Establishment

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IN-PLANE SHEAR PROPERTIES OF GRAPHITE FIBRE/EPOXY COMPOSITES FOR AEROSPACE APPLICATIONS:

EVALUATION OF TEST METHODS BY THE DECISION ANALYSIS TECHNIQUE

PROPRIÉTÉS DE CISAILLEMENT EN PLAN DE COMPOSITES FIBRES DE GRAPHITE/EPOXY POUR APPLICATIONS AÉROSPATIALES:

EVALUATION DES MÉTHODES D'ESSAIS PAR PRISE DE DÉCISION ANALYTIQUE

by/par

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SUMMARY

This review is the first phase of a study of Matrix dominated properties of advanced composites materials for aerospace application. In this report, all the commonly used in-plane shear test methods are examined and discussed in detail. Using a decision analysis technique, three test methods are selected for further study.

RÉSUMÉ

Cette revue est la phase première d'une étude des propriétés dictées par celles de la matrice de nouveaux matériaux composites pour applications aérospatials. On discute dans ce rapport de l'utilisation des diverses méthodes d'essai par cisaillement en plan. Grâce à une technique analytique de prise de décision on choisi trois méthodes d'essai pour des travaux futurs.

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1.0 INTRODUCTION

This review on the presently used in-plane shear test methods is the first phase of a study of matrix dominated properties of advanced composites materials for aerospace applications.

Of the many shear test methods available, some provide qualitative data while others provide quantitative data. Qualitative shear test methods are used mainly for quality control and material screening. They generally provide comparative values of shear modulus and shear strength. Quantitative shear test methods are used to accurately determine the complete shear stress-strain response of composite materials.

The ideal quantitative shear test method should provide a region of pure, uniform shear stress. In addition, there should be a unique relationship between the applied load and the magnitude of the shear stress in the test section. Further, for accurate determination of the shear stress-strain response, the test section should be one of maximum shear stress relative to all other regions of the specimen.

Based on the published literature, all the existing in-plane shear test methods are examined and discussed in detail in this report. This report also gives an assessment (using a decision analysis technique) of all the shear test methods and concludes that several test methods are suitable for the further study.

2.0 IN-PLANE SHEAR TEST METHODS

2.1 Introduction

The following sections present detailed descriptions and discussions of the major papers for each in-plane shear test method. Many investigators have evaluated and compared the various in-plane shear test methods for fibre composite materials. Since the various authors have not all compared the same test methods, some overlap occurs between the following sections.

2.2 Two and Three Rail Shear

The 2-rail shear specimen test and fixture (Figure 1) has been used quite extensively for advanced fibre composite materials in the aerospace industry. This method consists of clamping or bolting the long sides of a rectangular specimen to steel rails while the remaining sides are not constrained. The load is introduced at the ends of the rails to displace one rail parallel to the other.

Whitney[1] conducted an extensive theoretical stress analysis of the 2-rail specimen using a Fourier series solution. He concluded that this test method is valid for measuring the shear modulus of laminated composites provided that the length/width ratio is at least 10. For determining the in-plane shear strength, he found that an additional necessary condition is that the effective Poisson's ratio of the laminate with respect to the specimen edges should be less than unity. In the case of laminates having a high effective Poisson's ratio (such as 45° angle-ply composites) the shear stress distribution is very irregular and leads to extensively low values of shear strength as determined by this test method. He recommended that if this test method is used to obtain design allowables in shear, it must be used in conjunction with the proper laminate orientations or the designer will pay an unnecessary penalty by using values which are far too conservative thus resulting in over design of the structure.

A two dimensional linear elastic finite element model was used by Garcia[2] to analytically determine how various geometric parameters influenced the magnitude and distribution of in-plane normal and shear stresses in a 2-rail shear specimen. He concluded that: (1) the direction of loading (axial or diagonal) has little effect on stresses within the specimens, (2) the aspect ratio of the specimen can have a major effect on stress distribution (this varies according to the laminate) and (3) very high normal stresses occur perpendicular to the filaments in the 0° oriented specimen and, in fact, initiate premature failures relative to the 90° specimen.

Sims[3] believed that a better approximation to a state of pure shear can be obtained using the 3-rail shear test method (Figure 2) since the compressive load is applied parallel to the clamped edges of the specimen. Another advantage of this configuration is that two independent calculations of the shear stress-strain response can be made from one specimen.

Bergner[4] investigated the 3-rail shear test method by using finite element analysis and concluded that the rail configurations produce regions of uniform shear stress over most of the test sections for all laminates studied. However, this area of uniform shear stress was often accompanied by significant normal stresses depending upon the stiffness of the rails, the method of load application, and the laminate properties. Significant axial stress was always present in the test section for elastic rails axially loaded. The magnitude of this axial stress was approximately inversely proportional to the stiffness of the rails. Stress concentrations in the vicinity of the corners were found in all specimens.

Based on the results of the ASTM round robin on the 2 and 3-rail shear tests for laminated fibre composites[5], reported in 1981, Subcommittee D-30.04 on Composites made the following conclusions: (1) the variation in averages was great enough to cast doubt on the validity of the data as the tests are now run and (2) the spread of the data between the two test systems (2 or 3 rails) did not indicate a preferred test system.

2.3 ±45° Off-Axis Tensile

The ±45° off-axis tension coupon is a simple test specimen for obtaining the linear and nonlinear shear stress-strain response in the lamina co-ordinate axes. The specimen is a [±45°]s tension coupon [ASTM D-3518] usually with end tabs (Figure 3). Through the use of relations derived from laminated plate theory, Rosen[6] developed expressions which allow the in-plane 0° shear stress-strain curve to be generated from the longitudinal and transverse stress-strain curves obtained from a uniaxial tension test of the ±45° laminate.

The stress-strain results of a ±45° laminate test have been compared to those from the cross-beam test by Petit[7] (see para 2.5). He found close agreement between the two tests except for the nonlinear portion of the curve beyond the design allowable. He pointed out though that there were two approximations which were inherent with this test method. Firstly, since the laminate Poisson's ratio is not exactly 1.0 and hence ϵ_x is not quite equal to the negative of ϵ_y, the strain state at 45° to the x-y axes is not quite pure shear. Secondly, small tensile strains exist in addition to the relatively large shear strains in the principal directions of the laminae. This results in tensile stresses existing in the longitudinal and transverse directions of the laminae. Rosen[6] also suggested that the existence of an edge effect problem in the ±45° laminate requires care in the choice of the specimen width in order to obtain the desired accuracy of measurement.

Sims[3] found good agreement between the stress-strain response of ±45° tensile and 3-rail shear test specimens with glass fibre/epoxy composites. There was reasonably good agreement between the results of ±45° tensile tests and torsional tube tests (see para 2.7) performed by other workers for carbon fibre/epoxy composites.

Hahn[8] pointed out that the practice of equation $\frac{1}{2}\sigma_x$ to τ_{12} can be allowed only if there is no shear coupling (linear or nonlinear) even for symmetric laminates. He also concluded that the simple ±45° angle-ply will produce acceptable results provided that the layers are stacked in as homogeneous arrangement as possible.

Chiao[9] strongly recommended the ±45° specimen for determining the stress-strain response curve. He found good agreement with the tubular specimen up to failure. Based on the experimental results obtained in the study, they concluded that the ±45° tensile specimen has the following merits: good reproducibility, simple to make, is a conventional tensile test, economical in material, requires simple data reduction and is easy to test at high or low temperatures. Most of the above advantages were also verified by Greszczuk[10], Terry[11] and Yeow[12].

2.4 10° Off-Axis Tensile

The 10° off-axis tension coupon is another simple specimen similar in geometry to the [±45°]s tension coupon. The laminate is unidirectional with fibres oriented at 10° to the tensile load axis (Figure 4). A biaxial stress state occurs when a 10° off-axis specimen is subjected to a uniaxial tensile load. This biaxial stress state consists of three stresses: longitudinal, transverse and in-plane shear on the 10° plane. Chamis's[13,14] theoretical and experimental investigations led to the conclusion that when the 10° off-axis tensile specimen fails, the in-plane shear stress is near its critical value and he recommended the 10° off-axis tensile specimen for measuring in-plane shear strength of unidirectional fibre composites. Based on his study, he listed the following advantages of this test method: (1) specimens have uniform shear stress through the thickness, (2) can be adapted to testing for environmental and elevated temperature effects, (3) can be readily used for fatigue testing and dynamic and impact loading characterization, (4) specimens are free of laminate residual stresses and (5) the in-plane shear strain reaches or approaches its maximum value when the angle between the load and fibre directions is about 10° for graphite/epoxy composites.

The in-plane shear stress of the 10° off-axis tensile specimen is very sensitive to small misorientation errors. It is generally recommended that fibre direction, strain-gage positioning and load alignment be kept within ±1°. However, the misorientation is not critical if the fracture in-plane shear strain is sought since the strain peaks at a load angle of about 10° and is insensitive to small errors about this angle.

Yeow[12] has made a comparison of the shear responses for various test methods and concluded that an 10° off-axis test together with incremental lamination theory calculations is a reasonable approach to shear property determination. He suggested that the 10° off-axis test represents the best method of those investigated for the determination of the shear response of a ply or lamina.

Chiao[9] evaluated this method with aramid fibre/epoxy composite material and found that the 10° off-axis tensile shear test resulted in significant shear coupling and that it gave a higher shear modulus, lower failure stress, and lower failure strain than the ±45° off-axis laminate tensile shear test.

A theoretical investigation of the 10° off-axis tensile test method was conducted by Chamis and Sinclair[14] to study the fracture characteristics of unidirectional fibre composites subjected to an off-axis tensile load. The predicted results using composite mechanics were in very good agreement with measured data for modulus, Poisson's ratio, and shear coupling coefficient. However, the results obtained using the finite element analysis method indicated that the axial strain variation is very sensitive to out-of-plane bending and twisting eccentricities as small as about one ply thick. They recommended that the in-plane and out-of-plane effects should be taken into account in interpreting experimental data.

2.5 Cross-Beam Sandwich

The cross-beam shear specimen has been used for determining shear stress-strain response as well as ultimate shear strength values for fibre composite laminates. The cross beam shear specimen is loaded in positive and negative bending to produce a biaxial state of tension and compression over the test area at the centre of the specimen. The composite material facings are thin relative to the honeycomb core and thus are located at a large distance, relative to the facing thickness, from the mid-plane of the sandwich plate. The composite material is presumed to be subjected to an in-plane shear over the test section. Laminates commonly used with the cross beam are [0/90°]s and [±45°]s (Figure 5).

Fibre orientation and core reinforcement significantly influence the stress distribution present in the test section. The actual stress state predicted by analysis by Duggan et al[15] can deviate considerably from predictions based upon an elementary bending moment analysis. In a pure shear condition, the maximum shear stress planes must be free of normal stress. Analysis of the [±45°]s laminates of the cross-beam test[15] revealed significant normal stresses, resulting in errors of 13 to 20 percent in shear strength. Surprisingly, the normal stresses are greater in the test section than those applied away from that region. Duggan attributes this phenomenon to corner effects.

2.6 Picture Frame Panel

The specimen for this shear test (figure) consists of one or two thin, flat, square panels bonded to a honeycomb core material for stability. A rigid four bar linkage frame is then bolted or bonded to the panel for load introduction. In order to reduce high corner stresses these areas are usually cut out and have doublers bonded on or near the resulting free edges. The load is introduced by a combination of tension and/or compression forces in pairs on opposite corners (Figure 6). Thus, the specimen is subjected to shear loading along planes at 45° to the diagonals.

Bryan[16] made a photoelastic investigation of the stress distribution in the panels and found that the stress distribution deviated substantially from pure shear. Thus, the method is not appropriate for measuring the in-plane shear modulus. However, Bryan showed that at the critical region (which is along the edge) the stress state was essentially uniform pure shear and thus he recommended that this should be an accurate method for determining the in-plane shear strength.

Using a finite element analysis that included frame and nonlinear effects, Hadcock and Whiteside[17] tested boron/epoxy and borsic/aluminum picture frame specimens and reported that the corner stress concentrations nevertheless remained significantly high in both experiments. Dastin[18] reported that reliable initial shear modulus and ultimate strength values could be obtained from the picture frame specimen for fibreglass [0/90°]s laminates.

The panel must be sized to avoid buckling. The following expression for the applied diagonal force, necessary to buckle the panel, has been adapted from work by Davenport and Bert[19]: ($P_{cr} = 1.414\,\pi^2\,KD_y/a$) where a = length of panel side, Dy = transverse flexural rigidity of the panel, and K is a dimensionless buckling coefficient which depends upon D_x/D_y.

2.7 Thin-Walled Torsion Tube

Whitney[20] stated that the torsion tube is the most desirable specimen for determining shear stress-strain response from an applied mechanics standpoint. In this test, a thin-walled circumferentially wound cylindrical tube is subjected to a pure torque about its longitudinal axis (Figure 7). This subjects the wall of the specimen to a pure shear stress which is uniform around the circumference and along the length of the specimen. Since the wall thickness is small compared to the mean radius of the tube, the shear strain gradient through the thickness is negligible. In addition, the specimen has minimal normal stresses in the test section.

The stress distribution of the torsion tube specimen is very desirable, however, Rizzo and Vicario[21] reported that strength values may be influenced by gripping the ends of the tube. Thus, care should be taken to ensure that only pure torque is applied to the specimen, therefore, to prevent the development of bending moments, the specimen must be mounted concentrically. Axial forces that result as the specimen undergoes shearing deformation can be prevented by allowing one end of the specimen to move axially. The uniformity of the state of stress produced for tubular laminated specimens depends on the anisotropy as well as the geometry. Hahn[22] has found that the wall thickness to diameter ratio should be less than 0.03 to ensure fairly uniform stress distribution.

The main drawback to this specimen is the difficulty associated with fabricating and testing tubular specimens in which a sophisticated testing apparatus is required which is not available in most laboratories.

2.8 Slotted-Tensile Specimen

Duggan et al[15] proposed a new technique for determining the in-plane shear properties for arbitrary laminae orientations. In this test, standard tensile coupons are modified to provide shear specimens by adding two thin, axially oriented slots which terminate one inch apart along the centreline of the specimen (Figure 8). Tensile and compressive stresses are provided by applying axial and transverse loads in a ratio governed by the specimen width and the distance between the slots. The authors[15] have used the finite element method to calculate the slotted-tension coupon stresses resulting from mechanical loading and compared the results to the cross-beam specimen which was previously analyzed for two orthotropic cases. For the [±45°]s case, the authors reported that the shear stress in the slotted coupon test section is much closer to the ideal case. The stress in the area which was strain gauged was within 2% of the stress calculated from the applied load. The analysis indicates a shear stress concentration near the edge of the compression load pad, however, the error is less than expected for the cross-beam specimen. The authors[15] found that when a [0/90°]s laminate was tested the material failed in tension so the value obtained does not reflect a valid shear result. Very little data is available for evaluation of this new shear test method, thus, more studies are required.

2.9 Iosipescu's Method

This test method is relatively simple to conduct, employs small, easily fabricated specimens, and is capable of measuring both shear strength and stiffness. Nicolne Iosipescu of Rumania first proposed this test method in 1967.

The Iosipescu shear test (Figure 9) achieves a state of pure shear stress at specimen mid-length by applying two counteracting moments produced by forces couples. A state of constant shear force is induced through the middle section of the test specimen and the induced moments exactly cancel at the mid-length of the test specimen, thus producing a pure shear loading state at that location. The minimum section would have to be at the centreline to obtain maximum shear stress at that location. Such a condition was achieved by Iosipescu[23] in metal specimens machined with 90° vee notches at the top and bottom edges, leaving a net section depth at the specimen centreline of one half of the overall depth. Iosipescu confirmed the uniform state of pure shear by means of photoelastic strain field measurements on plexiglass models. The uniform stress state apparently results from the coincidence of the principal stress directions at ±45° to the specimen axis with the 90° notch angle in the region of zero bending stress. There is no stress singularity at the notch root because of the absence of normal stresses at this point.

Iosipescu's investigation was concerned only with homogeneous, isotropic materials. Finite element analysis carried out by Slepetz[24] confirmed the parabolic and uniform stress distributions in the isotropic specimen. However, it also indicated that in the case of composites, the stress distribution deviates somewhat from ideal conditions and may in fact be dependent on material properties. There is a significant stress concentration found at the notch root in unidirectional laminates and it is believed that shear coupling deformations along the notch flank impose a redistribution of stresses at the notch section, resulting in concentration at the root. Bergner[4] reported that bonding suitable doublers to the corners and rounding the notch tips can reduce the stress concentrations in critical areas.

Adams's[25] results for sheet molding compound (SMC) composite materials showed that the Iosipescu shear test works well for determining the in-plane and through-the-thickness shear strength of SMC. The shear modulus results obtained for the various SMC materials tested agreed well with values obtained by other investigators using different test methods. Shear strength results obtained with the Iosipescu shear test were somewhat higher than those obtained with the rail shear tests.

This test method is not limited to in-plane shear measurements of composite materials. It could be used to determine interlaminar shear properties of laminates and would also appear to be useful for measuring the shear strength of adhesive joints.

2.10 Other Types of In-Plane Shear Tests

The cross section of composite laminates can experience a twisting type of shear deformation. Bert[38] has carried out a thorough review of this kind of shear loading and he classified the test methods into four main types (1) Plate Twist, (2) Torsion Strip, (3) Torsion Bar and (4) Split Ring.

A special loading fixture is required for the plate twist specimen (Figure 10a). The method is effective for determining shear modulus, however, shear strength is difficult to obtain from this method because the ultimate load required may cause excessive indentation or failure near the loading points. The torsion strip test was first suggested for testing metallic materials by Dai[26] in 1965, and was applied to unidirectional glass/epoxy composites by Bracco[27] in 1971. A double-strip test was also suggested by Slepetz[39], however, this test method was not so popular and has not yet been fully evaluated. The torsion bar method has only been used by Adams[28] to investigate S-glass/epoxy composites using both molded and machined specimens. The cross-sections were both round and square. In reducing the test data, the correct equations from anisotropic elasticity theory must be properly used. A split ring loaded out of plane (Figure 10b) test was originated by Greszczuk[29] and was intended to be used only for orthotropic rings. Guess and Bert[30] extended the data reduction procedure so that it is applicable to many layered bihelically wound rings. Good agreement was obtained by comparing the shear modulus results with those obtained from torsion tube tests. These other types of in-plane shear tests were included for completeness, however, since they are seldom used, they were not evaluated by the decision analysis technique in the next section.

3.0 EVALUATION OF TEST METHODS BY THE DECISION ANALYSIS TECHNIQUE

3.1 Introduction

The objective of this review is to evaluate the more commonly used test methods for measuring the in-plane shear stress-strain response of advanced composite materials. It is generally recognized that an ideal test method is one which is relatively simple to conduct, requires small, easily fabricated specimens, and is capable of measuring both shear strength and shear stiffness simultaneously. It is difficult, however, to devise a test method which incorporates all of the above.

The detailed discussion of the major test methods for measuring in-plane shear properties in the previous sections indicates the types of problems which may be encountered and the limitations of each test method. Comparing these factors is very difficult in some aspects. For some test methods, factors which are less important for some become dominant for others. Considering other factors such as cost of materials, cost of testing, and specimen fabrication, and testing equipment required leads to the conclusion that no one test method can be considered best for all applications.

In order to evaluate the test methods for this study from as wide a base as possible, a decision analysis technique has been used. This technique is very useful for the difficult task of evaluating a large number of solutions against a large number of criteria. It allows for assignment of quantitative ratings based upon subjective evaluations. In this section the nine major in-plane shear test methods have been evaluated with respect to eleven criteria covering the major areas of cost of fabrication, cost of testing, data producibility and accuracy of experimental results. Each test method is numerically rated on a relative basis from 0 to 10 for each criterion. Each criterion is assigned a weight between 0 and a maximum of 200 depending upon how important the authors consider each criterion relative to the others. The criterion score for a test method is the product of the numerical rating and the weight; the total score for the test method is the sum of all of these products. The actual ratings for this study are given in Table I. The next section discusses the reasons for selecting the individual criteria, their respective weights, and the more critical relative rankings for each test method with respect to the individual criteria.

3.2 Decision Analysis

3.2.1 Criteria Weighting

At present, advanced composite materials are relatively more expensive than conventional metallic materials. However, the quantities required for making the experimental test coupons are usually small, so the material costs are not a significant factor compared with other factors. Thus, the material quantity criterion is assigned a weight of 20. Because of the difference in the specimen geometry of the different test methods, special processing techniques are required for fabrication. Some of these are costly and time-consuming with the result specimen processing is weighted at 40. The quality of the machined specimen is important and critical as any damage to the specimen (micro-cracking or delamination) during preparation can lead to unreliable test results. Since the test specimens for all test methods are different in geometry, special machining equipment and techniques are usually required for preparing the specimen with, in some cases, special trimming fixtures. Thus, the specimen preparation criterion also received a weight of 40. There are two major processes to manufacture advanced composite materials: prepreg layup and wet filament winding. The prepreg materials cured in an autoclave always yield laminates with better controlled thicknesses and lower void contents. The physical properties of advanced composite materials made with the wet filament winding technique are relatively more difficult to control. The processing criterion is weighted at 50.

Testing equipment plays a very important role in in-plane shear testing. For some types of specimens, the universal test machines are simply not adequate to perform the testing because of the requirement of non-standard loading directions. The testing equipment criterion received a weight of 100. In order to conduct the testing using universal test machines, special testing fixtures are required for some test methods so that loads can be applied at certain areas of the specimen. Handling, test procedures and testing time for different test methods vary greatly. Auxiliary instrumentation is required for some test methods in order to obtain the desired measurements. Each of these three final criteria were assigned a weight of 50.

Since the primary objective of all the in-plane shear test methods is to measure the strength and the stiffness of advanced composite materials, these two criteria are essentially the most important and they are each weighted at 150.

Any useful or meaningful results obtained from experimental work not only rely on the accuracy of measurements and the interpretation the test data but also depend on the reliability of the test method. It is generally agreed that the thin-walled tube torsion test method is one of the most desirable test methods to determine the in-plane shear properties of composite materials. It is being used as a reference by many investigators to evaluate other shear test methods. The accuracy of the experimental results (with respect to the thin-walled tube specimen results) was thus assigned a weight of 200.

3.2.2 Test Method/Criteria Rating

The rating assigned to each of the nine test methods for each of the eleven criteria are given in Table I. In the following sections on cost of fabrication, cost of testing, data producibility and accuracy of experimental results, some of the more noteworthy ratings are discussed.

3.2.2.1 Cost of Fabrication

Material Quantity: The thin-walled tube specimen was assigned a very low rating of 1 for the material quantity criterion because the amount of material required for the tube specimen is much more than for the others. The tubes must be long enough to permit the attachment of end plugs for load application and thick enough to minimize handling damage. Due to the size of the complete cross-beam sandwich specimen, a considerable amount of material is required for the specimen, with the result that it was rated at 2. The 10° off-axis tensile shear specimen requires the least amount of material and was assigned a rating of 10.

Processing Equipment: The thin-walled tube and the cross-beam shear test methods were rated at 8 because of their more complicated geometrical configurations. The remainder of the other test methods were rated at 10.

Specimen Processing: Filament winding or special lay-up techniques are required to fabricate the thin-walled tube specimens, therefore, the tube specimen was rated at 2. The other flat specimens fabricated with conventional hand lay-up techniques were rated at 9 or 10.

Specimen Preparation: In the rail shear tests, specimens are clamped or bolted to the test fixture. To properly align the specimen with the loading direction, a pattern of holes is introduced to the specimen using a special drilling fixture and tools, thus, the rail shear specimen was rated at 6. Because of the relatively simple preparation required, the flat coupon type specimens were rated at 10. The remainder of the test methods were rated at 7 or 8 depending on the test fixture configurations.

3.2.2.2 Cost of Testing

Testing Equipment: The thin-walled tube specimen was rated at 2 because of the requirement of a torsion device to perform the testing, while the other test methods require only a universal test machine.

Special Fixture: The 10° off-axis tensile shear and the ±45° tensile shear do not require any testing fixture and were each rated at 10 in the special fixture criterion. The others were each rated differently, depending on the complexities of their testing fixtures.

Specimen Testing: The thin-walled tube specimen, cross-beam sandwich specimen, and both the slotted-tensile and the picture frame specimen were rated at 2, 3, and 4, respectively because of the set-up and actual testing time required are much more than for the rest.

Auxiliary Instrumentation: Most of the test methods were rated at 10 in the auxiliary instrumentation criterion except for the thin-walled tube and the slotted-tensile specimens. Dial gauges and strain gauges are usually required for these two test methods.

3.2.2.3 Data Producibility

The nature of the shear stress induced in each test method is dependent on the geometry of the specimen. Based on the data published in past years (reviewed in detail in Section 2), each in-plane shear test method is now briefly summarized. For the rail shear tests, Lockwood[5] reported that the spread between the two test systems did not indicate a preferred system and the wide variation in the average values casts doubt on the validity of the data. The 10° off-axis tensile test method[9] showed that the shear modulus is about 19% higher and the fracture stress is about 38% lower than that of the thin-walled tube torsion test. Whitney[1] found that this test resulted in significant shear coupling. Chamis[13] indicated that the test results from the 10° off-axis tensile specimen are within the range of the values reported elsewhere. He also pointed out that the spread in the available data is due to variations in fibre volume ratio. Chiao[9] evaluated the ±45° off-axis laminate tensile shear test with aramid/epoxy material and found a shear modulus about 10% higher and a shear failure stress about 6% lower than that of the thin-walled tube torsion. He concluded that the ±45° off-axis laminate tensile shear test was simple and reproducible. The cross-beam sandwich laminate tests[15] revealed significant normal stresses resulting in errors of 13 to 20 percent. Due to corner effects, the stresses are greater in the test section than those applied away from that region, so the data obtained from this test is not as reliable. Several investigators reported that the corner stress concentrations are significantly high and only the initial shear modulus and ultimate strength values are reliable from the picture frame specimens. The slotted-tensile test is a new method being studied by Duggan[15]. His results indicate that this test method works well for a certain number of materials. However, further analytical studies are required to fully investigate the effect of specimen geometry. Since the torsional shear of a thin-walled tube can produce the desirable state of pure shear, many researchers have used this test method as a reference base for other shear test methods. On the other hand, it is not a simple test that can be easily used. The Iosipescu test method has been studied in detail by Bergner[4] with the finite element method. He found that the specimen is one of the most suitable for the determination of the in-plane shear response of composite laminates. Adams[25] also reported that the shear modulus results obtained for various sheet molding composite materials agreed with values obtained by other investigators using different test methods. Also, shear strength results obtained with the Iosipescu test method were somewhat higher than results obtained with the rail shear test.

From an applied mechanics point of view, torsion of a thin-walled tube provides a means of directly applying pure shear to the composite specimen. The thin-walled tube specimen was therefore rated at 10 for the stiffness and strength criteria. The 2-rail shear and cross-beam sandwich test methods were each rated at 6 in the strength criterion, mainly because the free edge and corner effects, respectively. Most of the test methods were assigned a rating of 7 or 8 in the stiffness criterion except for the picture frame specimen. The picture frame specimens usually experience buckling under load and thus give unreliable data.

3.2.2.4 Accuracy of Experimental Results

There are a number of test methods available for the determination of the shear stress-strain response of advanced composite materials and most of the aforementioned are frequently used today. However, many of them produce quantitative results which are questionable. The uncertainty of obtaining a state of pure shear is the main problem. It is generally agreed that torsion of a hoop-wound, thin-walled tube produces the desired state of stress and strain and provides both shear strength and stiffness data[33,34,37]. Since the hoop-wound, thin-walled tube specimen is considered to be the most reliable test method for determining the shear stress-strain response, investigators often use the results of this test method as a standard for comparison. Some of the published experimental results for various shear tests tested in Section 2 are again reviewed. Sims[3] determined graphite/epoxy shear properties using the rail-shear test method and compared the results to the torsion tubular specimen test. He found that the shear stress-strain response agreed well in the useful strain level (below the allowable design limit). Garcia[2] reported that the rail-shear test method gives a conservative ultimate strength. Chiao[9] compared the ±45° off-axis laminate tensile shear test results for aramid/epoxy composites to those of the thin-walled tube torsion test and found that the ±45° off-axis tensile shear test results in a 10% higher shear modulus and a 6% lower ultimate strength. Sims[3] also compared the ±45° off-axis tensile shear test method with published thin-walled tube torsion data for graphite/epoxy composites and found good agreement in shear stress-strain responses. For the 10° off-axis tensile test, Chamis[14] compared the experimental results to several shear test methods including the thin-walled tube torsion and concluded that the shear stress-strain responses were in good agreement. Lenoe[35] used several shear test methods to characterize graphite/epoxy composite materials and reported that the shear strength obtained from the cross-beam shear test is 30% lower than that of the thin-wall torsion test. No specific experimental data for the picture frame shear test in comparison with the torsion tube shear test can be found in the literature. Dastin[18] found that reliable initial shear modulus and ultimate strength values could be obtained from the picture frame test method. Duggan[15] reported that the shear modulus determined by the slotted-tension test method did differ by 10% as compared to the thin-walled tube torsion test. He pointed out that a final assessment of the validity and accuracy of this technique must be further studied. Adams[25,36] has used the Iosipescu shear test to determine the shear properties of several different composite materials. He found that the shear modulus agreed well with the values obtained by other investigators using different test methods. The shear strength results obtained with the Iosipescu shear test were somewhat higher than results obtained with the rail shear tests.

In light of the above discussion, the thin-walled tube torsion test was assigned a rating of 10 and the other tests were evaluated with respect to it. The ±45° off-axis tensile, 10° off-axis tensile and Iosipescu all received very good ratings of 9 with the remainder of the other test methods evaluated at 7 or 8.

3.2.3 Total Rating Scores

Table I provides the details of the Decision Analysis Rating. High numerical scores indicate promising test methods for this study. The top three are Iosipescu, 45° off-axis tensile and 10° off-axis, respectively. They have very similar scores with the next test method (3-rail shear) being significantly lower. The thin-walled tube specimen has been frequently used as a key reference test method by many investigators for evaluating other test methods. Despite its low score and 8th place ranking in the table, it seems reasonable that for the experimental portion of this study a few thin-walled tube specimens should be fabricated from the same batch materials and tested. The data can then be compared and correlated with other results obtained for the three selected test methods.

4.0 CONCLUSION

The first part of the study, as detailed in this report, is concerned with the review and subsequent evaluation of essentially all available in-plane shear test methods. By using a decision analysis technique, the three most promising test methods were selected for the determination of the in-plane shear response of three graphite/epoxy fibre composite materials suitable for primary structure aerospace applications. A second report will present the correlation of the experimental results between the four test methods.

5.0 ACKNOWLEDGEMENT

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TABLE I

EVALUATION OF IN-PLANE SHEAR TEST METHODS

BY THE DECISION ANALYSIS TECHNIQUE

Criterion / Weighting (Rating) — In-Plane Shear Test Method	Cost of Fabrication				Cost of Testing				Data Producibility		Accuracy of Experimental Results	Total Score	Rating
	Material Quantity	Processing Equipment	Specimen Processing	Specimen Preparation	Testing Equipment	Special Fixture	Specimen Testing	Auxiliary Instrumentation	Strength	Stiffness	Comparison With Thin-Walled Tube Experimental Results		
	20 (10)	50 (10)	40 (10)	40 (10)	100 (10)	50 (10)	50 (10)	50 (10)	150 (10)	150 (10)	200 (10)		
1) 2-Rail	7	10	10	6	10	5	10	10	6	7	7	6880	7
2) 3-Rail	6	10	10	7	10	4	10	10	7	7	8	7200	4
3) 45° Tensile	9	10	10	10	10	10	10	10	7	8	9	7905	2
4) 10° Off-Axis	10	10	9	10	10	10	10	10	7	7	9	7860	3
5) Cross-Beam	2	8	7	8	7	7	3	10	6	7	6	5890	9
6) Picture Frame	4	10	10	8	10	6	4	10	7	6	7	7150	5
7) Thin-Walled Tube	1	8	2	7	2	2	2	7	10	10	10	6530	8
8) Slotted — Tensile	8	10	10	7	10	3	4	8	8	8	7	6890	6
9) Iosipescu	9	10	10	10	10	7	10	10	8	8	9	8030	1

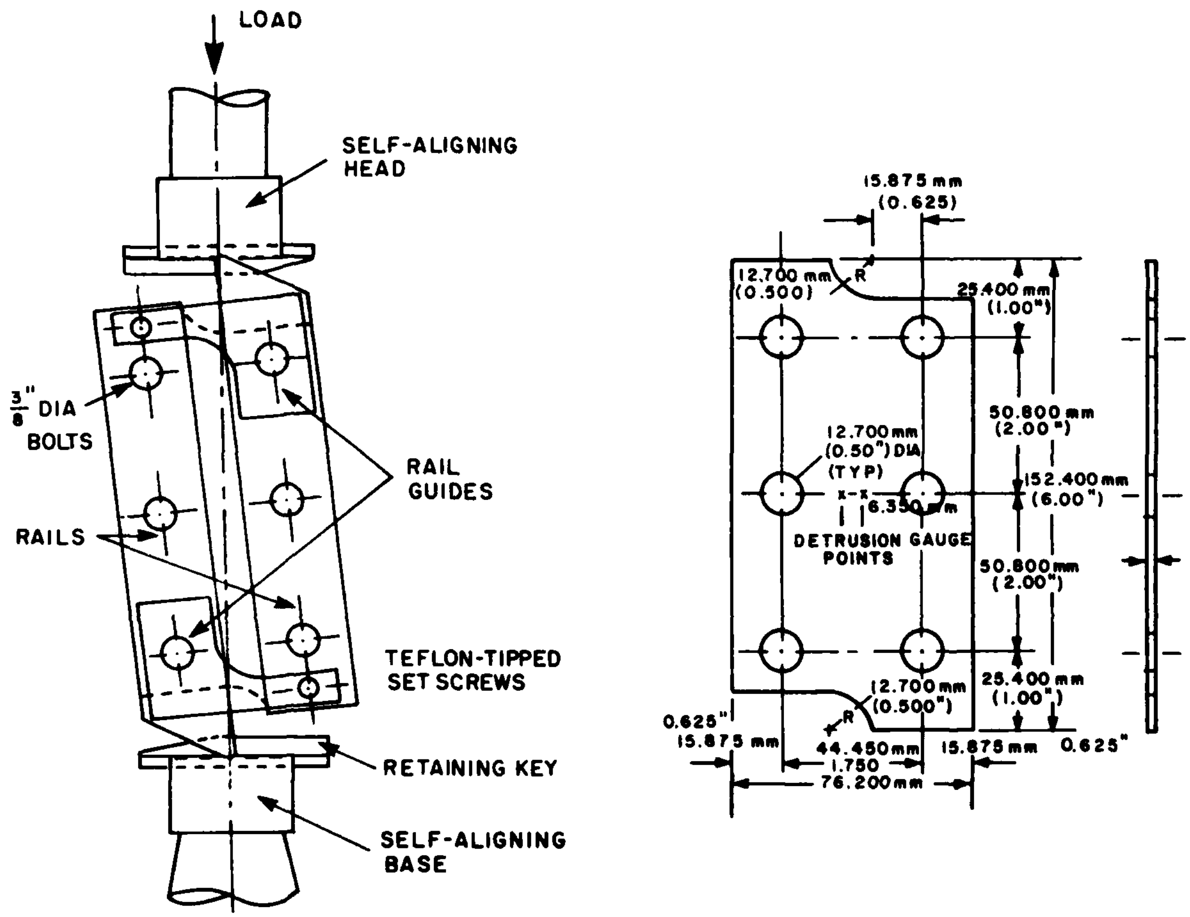

FIG. 1: TWO-RAIL SHEAR APPARATUS AND SPECIMEN (ASTM D4255)

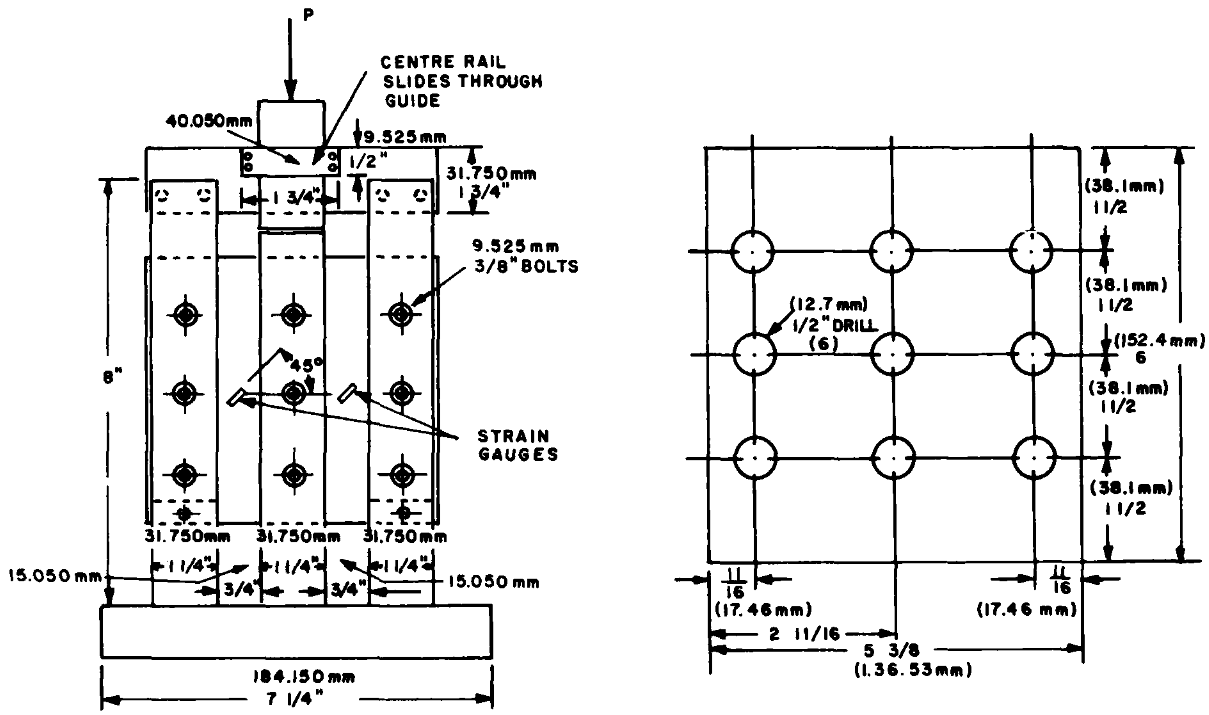

FIG. 2: THREE-RAIL SHEAR APPARATUS AND SPECIMEN (ASTM D4255)

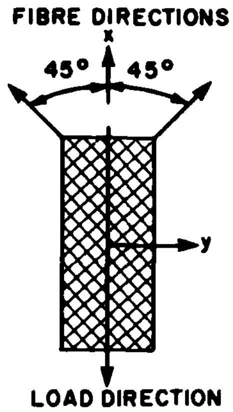

FIG. 3: ±45° OFF-AXIS TENSILE SPECIMEN (ASTM D3518)

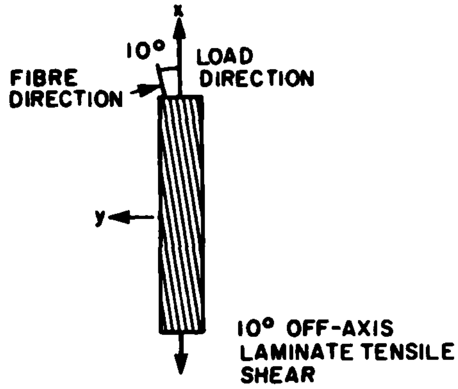

FIG. 4: 10° OFF-AXIS TENSILE SPECIMEN[13]

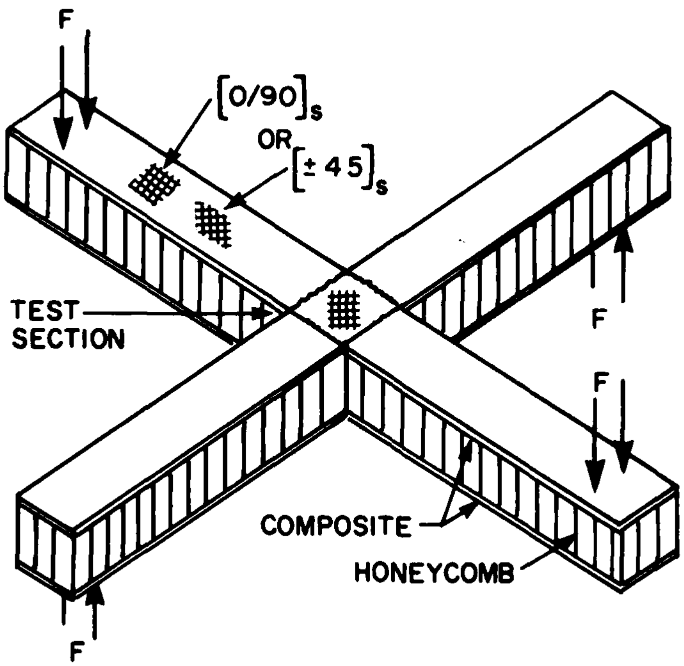

FIG. 5: CROSS-BEAM SANDWICH SPECIMEN[15]

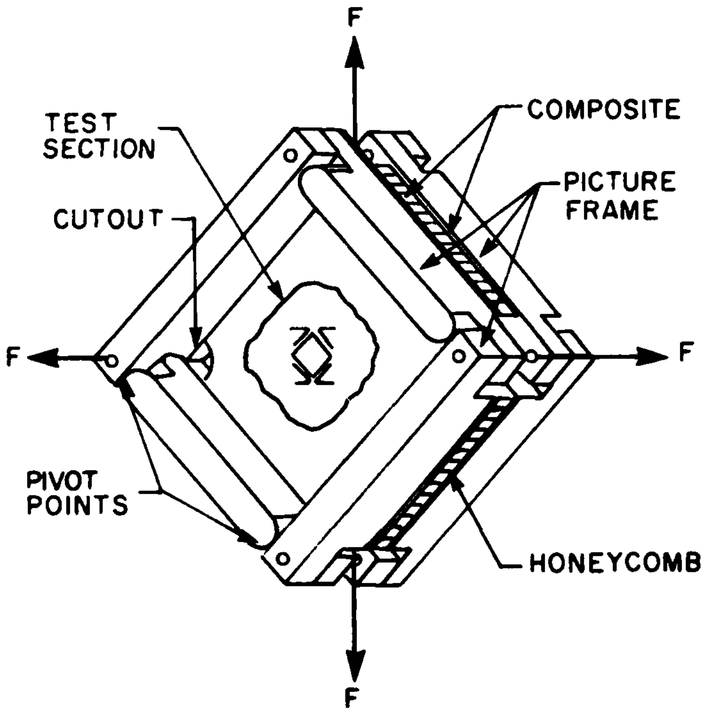

FIG. 6: PICTURE FRAME PANEL LOADING FIXTURE AND SPECIMEN[16]

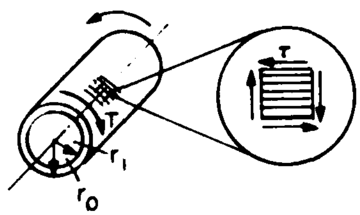

FIG. 7: THIN-WALLED TORSION TUBE

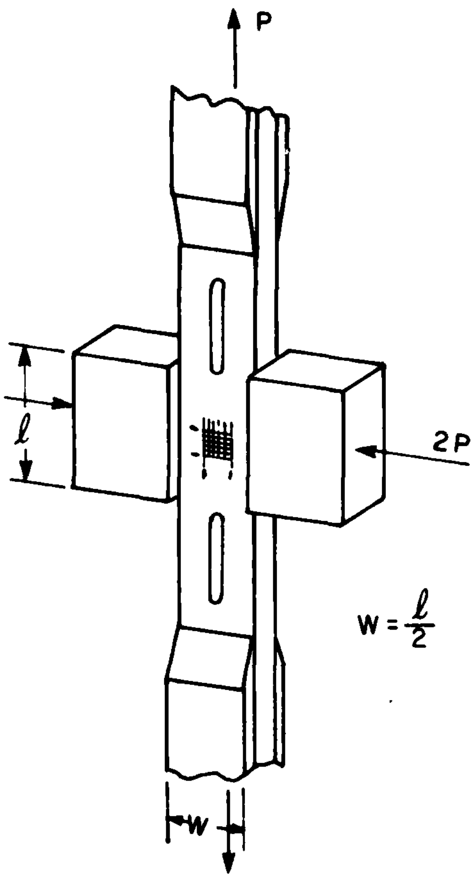

FIG. 8: SLOTTED-TENSILE SPECIMEN[15]

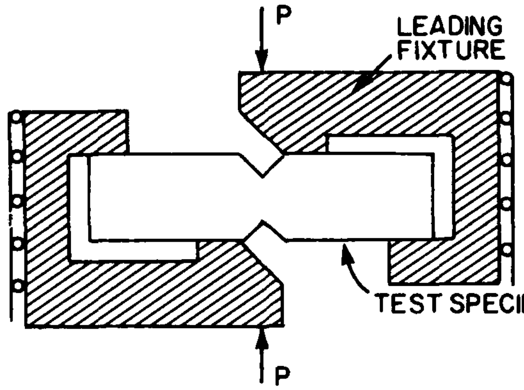

FIG. 9: IOSIPESCU'S TESTING FIXTURE AND SPECIMEN

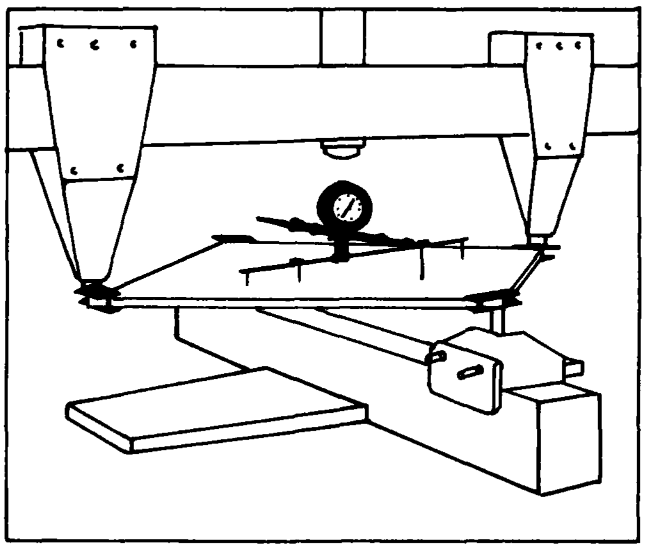

FIG. 10a: PLATE TWIST TEST SET-UP[40]

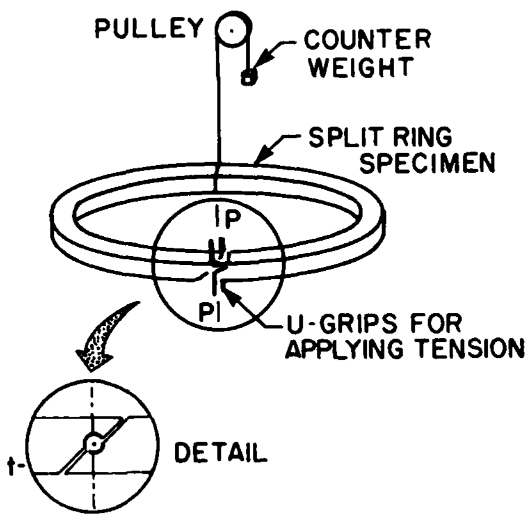

FIG. 10b: SPLIT-RING TEST SET-UP[29]

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In-Plane Shear Properties of Graphite Fibre/Epoxy Composites for Aerospace Applications:

4 Evaluation of Test Methods by the Decision Analysis Technique

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NOTES

13

DESCRIPTORS (KEY WORDS)/MOTS-CLÉS

1. Composite materials
2. Graphite fibre/epoxy composites

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SUMMARY/SOMMAIRE

This review is the first phase of a study of Matrix dominated properties of advanced composites materials for aerospace application. In this report, all the commonly used in-plane shear test methods are examined and discussed in detail. Using a decision analysis technique, three test methods are selected for further study.

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