Progress Report

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MECHANICALLY FASTENED JOINTS

IN WOVEN FABRIC COMPOSITES

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RESEARCH OBJECTIVES

A comprehensive investigation of the behavior of bolted joints in woven fabric composites was proposed as outlined by the following research objectives:

1) The experimental evaluation of the effects of fabric construction, material properties, laminate configuration and joint geometry on the strength and failure mode of woven fabric composites through a joint effort with NASA Langley Research Center.

2) The formulation of failure models consistent with the failure characteristics exhibited for each of the three primary modes, net tension, shearout and bearing.

3) The development of a complete bolted joint failure analysis for woven fabric composites through the coupling of mode specific failure criteria with an accurate stress analysis.

This interim report summarizes the progress attained in meeting these research objectives during the first six months of the research grant.

INTRODUCTION

Traditionally, the design and analysis of composite bolted joints has relied heavily on empirical data for the specific material system, laminate configuration and joint geometry desired. For years, substantial effort has been devoted to the development of more sophisticated stress analyses, while few satisfactory advances in failure criteria have been proposed. Recently, significant advances have been made in the area of failure criteria for composite bolted joints [1-10], with resultant improvements in the accuracy of strength analyses. The ultimate objective is the development of a bolted joint strength analysis which requires only intrinsic material properties, thus eliminating the need to develop large empirical bolted joint data bases.

The development of any new strength analysis requires verification by comparison with experimental results. The current research program has been designed to simultaneously develop analytical failure criteria for the three primary failure modes (net tension, bearing and shearout), and generate the experimental data for the verification of these failure models over meaningful ranges of the parameters which influence bolted joint strength.

2

EXPERIMENTAL PROGRAM

The goal of this portion of the research program is experimental characterization of the behavior of bolted joints in woven fabric composites. The overall program involves the generation of three data sets. First, basic material properties must be characterized. Second, the effects of fabric construction, laminate configuration and joint geometry on strength and failure mode must be determined experimentally. Lastly, the notched strength behavior of the system must be experimentally evaluated. The results from these three test programs form the empirical data base necessary for the bolted joint strength analysis program and its verification.

TEST PROGRAM

The experimental program was fully detailed in the program proposal. For convenience, the summary of the test matrix is reproduced in Tables 1 and 2. Table 1 outlines the bolted joint tests which investigate the following important parameters: laminate configuration, stacking sequence, fastener diameter, edge distance, fastener half spacing, laminate thickness and fastener torque. Table 2 summarizes the notched strength test program which investigates the influence of laminate configuration, notch size and laminate thickness on strength.

Table 1.   Proposed Bolted Joint Test Program

Test Variable	Configuration
Laminate Configuration	$[0/90/\pm45/\pm45/0/90]_{ns}$
	$[\pm45/0/90/0/90/\pm45]_{ns}$
Fastener Diameter	0.500 in. (12.7 mm)
	0.375 in. (9.5 mm)
	0.188 in. (4.8 mm)
Edge Distance (e/D)	4.0
Fastener Half Spacing (w/D)	3.0
	6.0
Fastener Torque	15 in-lb
	30 in-lb

Table 2. Notched Strength Test Program

Laminate	Thickness (in.)	Hole Size (in.)	No. Specimens
$[0/90/\pm45/\pm45/0/90]_{2s}$	.128	.125	3
	.128	.250	3
	.128	.375	3
	.128	.500	3
$[0/90/\pm45/\pm45/0/90]_{6s}$	.384	.125	3
	.384	.250	3
	.384	.375	3
	.384	.500	3
$[\pm45/0/90/0/90/\pm45]_{2s}$	.128	.125	3
	.128	.250	3
	.128	.375	3
	.128	.500	3
$[\pm45/0/90/0/90/\pm45]_{6s}$	.384	.125	3
	.384	.250	3
	.384	.375	3
	.384	.500	3

SPECIMEN FABRICATION

At the request of NASA, Hercules AS4/2220-3 rubber toughened graphite epoxy material was chosen for the program. Plain weave fabric (3k fiber tows) prepreg has been procured for laminate fabrication using standard layup techniques.

Based on the test matrix, which calls for 264 tests, the set of laminates summarized in Table 3 have been designed to meet the test program requirements. In addition, a set of [0/90]* and [±45]* laminates were fabricated for the basic property characterization tests. About 60-70 percent of the bolted joint and notched strength laminate panels have been fabricated (layed up and cured), and another 10-15 percent layed up.

Processing of the AS4/2220-3 fabric-based system encountered problems not initially mentioned by the manufacturer. The standard cure had to be modified to a "no bleed" process in order to obtain the desired laminate quality and surface smoothness. Aluminum caul plates were used on top and bottom surfaces. The modified cure schedule and bagging

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*These laminates were layed up such that warp and fill directions were always aligned in the same direction.

Table 3. Stacking Sequence/Cured Thickness

Laminate Code	Stacking Conf.	Cured Thickness
I_a	$[0/90/\pm45/\pm45/0/90]_s$	0.064
I_b	$[0/90/\pm45/\pm45/0/90]_{2s}$	0.128
I_c	$[0/90/\pm45/\pm45/0/90]_{3s}$	0.192
I_d	$[0/90/\pm45/\pm45/0/90]_{4s}$	0.256
I_e	$[0/90/\pm45/\pm45/0/90]_{5s}$	0.320
I_f	$[0/90/\pm45/\pm45/0/90]_{6s}$	0.384
I_g	$[0/90/\pm45/\pm45/0/90]_{9s}$	0.576
II_a	$[\pm45/0/90/0/90/\pm45]_s$	0.064
II_b	$[\pm45/0/90/0/90/\pm45]_{2s}$	0.128
II_c	$[\pm45/0/90/0/90/\pm45]_{3s}$	0.192
II_d	$[\pm45/0/90/0/90/\pm45]_{4s}$	0.256
II_e	$[\pm45/0/90/0/90/\pm45]_{5s}$	0.320
II_f	$[\pm45/0/90/0/90/\pm45]_{6s}$	0.384
II_f	$[\pm45/0/90/0/90/\pm45]_{9s}$	0.576

technique was discussed with Hercules and found to be identical to practices used by them for the cure of woven fabric 2220-3 composite systems. The cure schedule is given below:

1. Place prepreg in vacuum bag, then in autoclave, and apply full vacuum.

2. Apply pressure to 70-80 psi.

3. Vent vacuum to atmosphere at approximately 20 psi.

4. Begin heating at 3-5°F/min.

5. Hold temperature at 350°F for 2 hours.

6. Cool to 200°F in 40 min. or more under pressure (pressure may be decayed as temperature decreases).

7. Release pressure and remove from autoclave.

Individual test specimens are fabricated from the panels using standard techniques. Diamond wafering saws and diamond core bits are employed in trimming specimens to size and boring fastener holes. Specimen fabrication for the material property study has been completed. Fabrication is ongoing for the bolted joint and notched strength studies.

TEST METHODS

The material property characterization study was conducted to measure the basic strength and stiffness of the AS4/2220-3 material in the warp and fill directions and in shear. Standard ASTM methods were employed [11-13] for the tension, compression and shear testing. Three replicates were tested for each property. Results are given in Table 4 for the tension and compression tests. The shear response tests have not been completed yet.

Only slight differences were measured between the warp and fill directions for either tension or compression properties. It is significant to note that the compressive properties, stiffness and strength are significantly lower than the tensile properties. The difference can be attributed to the woven fabric undulations, which amplify instability of the fibers and reduce the properties. The lower strength coupled with lower stiffness could result in interesting effects on the bearing strength of the material in a bolted joint.

None of the bolted joint testing has been completed yet. Bolted joint strength and failure modes will be measured using a single fastener, double lap joint configuration

Table 4. Tension and Compression Properties of the
          AS4/2220-3 Plain Weave Fabric

Description	Modulus Msi	Strength Msi	ν_{12}	Max. Strain Est. %
Tension (warp)				
BJT1A	9.52	116.3	.063	1.24
BJT1C	8.83	122.8	.036	1.38
BJT1D	9.52	120.6	.050	1.28
Tension (fill)				
BJT2A	9.10	122.9	0.027	1.33
BJT2B	9.49	126.5	0.050	1.36
BJT2C	9.23	123.6	0.031	1.34
Compression (warp)				
BJC1A	8.04	97.1	—	
BJC1B	7.86	89.5	—	
BJC1C	7.97	108.1	—	
Compression (fill)				
BJC2C	7.93	85.3	—	
BJC2D	7.77	80.9	—	
BJC2E	7.85	94.6	—	

(Figure 1). A sketch of the fixture to be employed is shown in Figure 2. Metal plates are used to transmit load between the load cell and the bolted joint. Washers of known area will be placed between the metal links and the specimen. A fastener inserted through the double lap joint will be tightened to one of the two specified torques. The fit between the washer and the fastener and the specimen and the fastener will be closely controlled and quantified. The joint will be monotonically loaded to failure while recording the load versus extension behavior. The failure load will be designated as the maximum load carried by the joint before the material ceases to carry load.

Notched strength tests have not yet been performed, but will be conducted using standard tension test methods. Each specimen has been fabricated to the 2 inch wide by 9 inch long geometry shown in Figure 3. Specimens will be monotonically loaded to failure while recording the load extension characteristics.
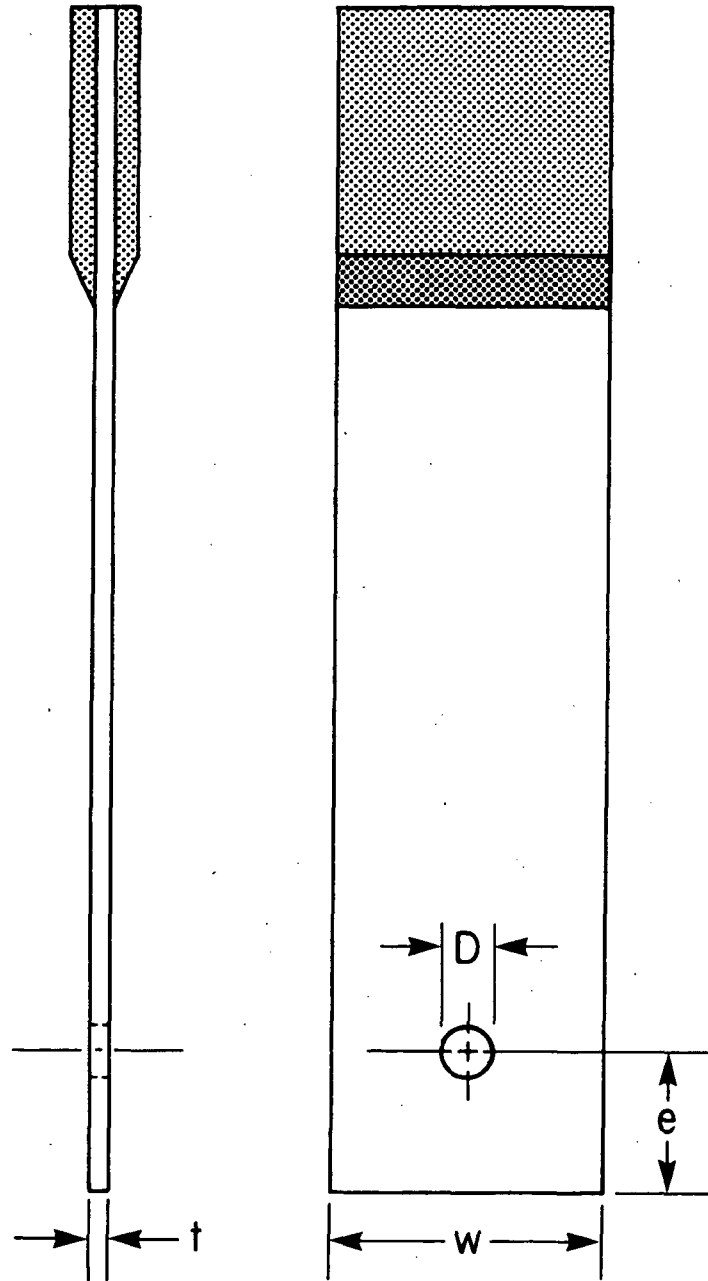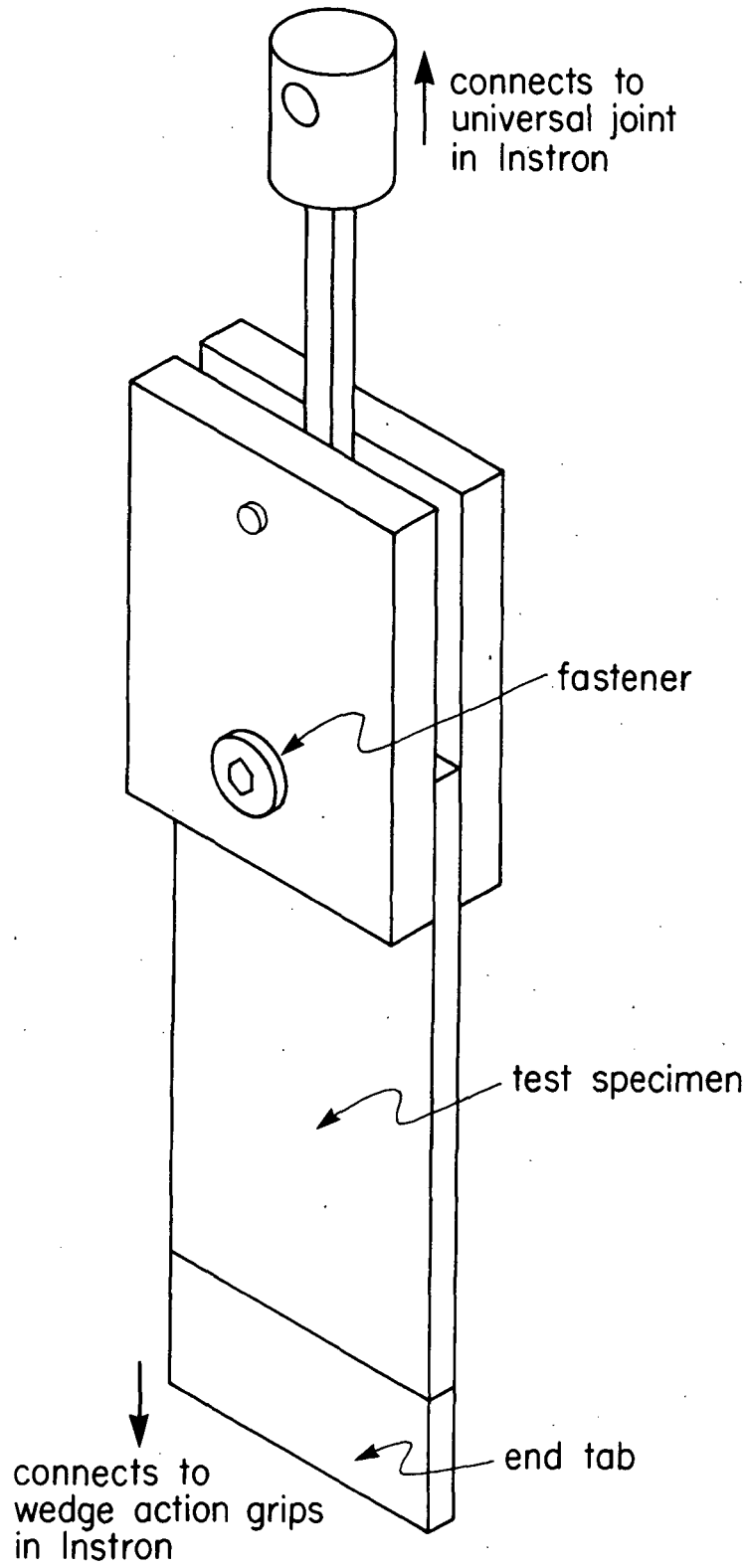
Figure 1. Bolted Joint Specimen

connects to
universal joint
in Instron

fastener

test specimen

end tab

connects to
wedge action grips
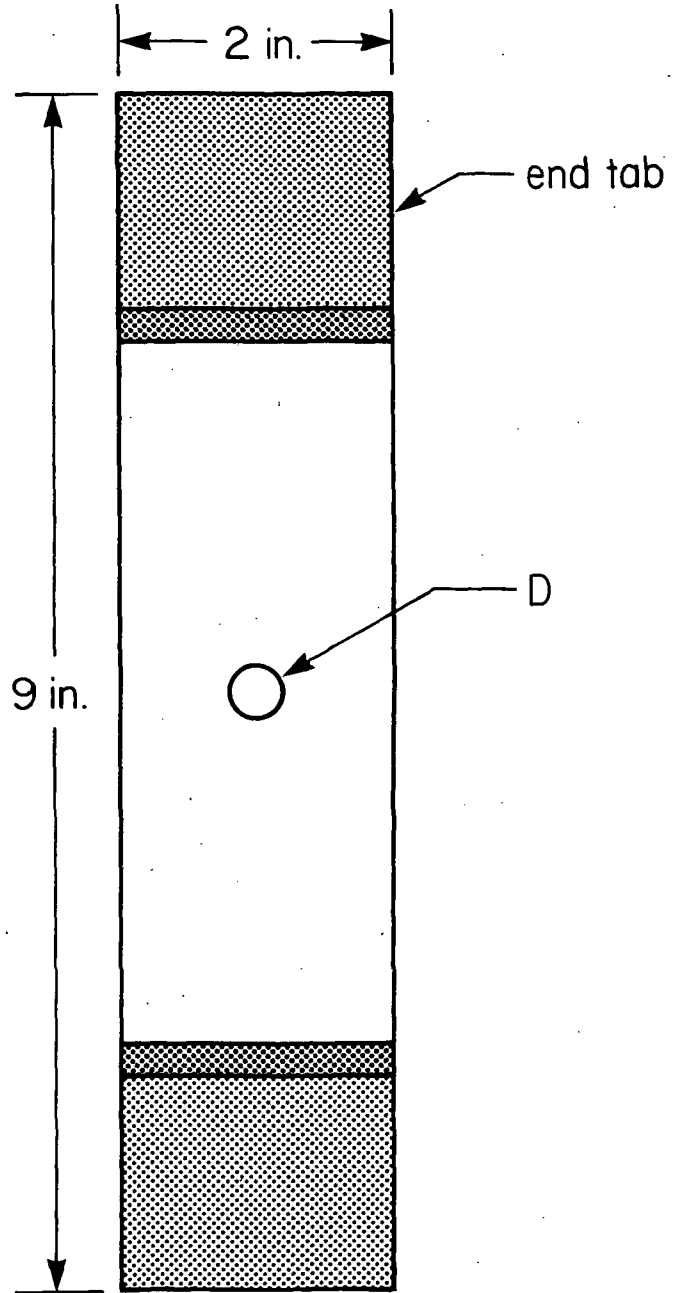in Instron

Figure 2. Bolted Joint Test Fixture

Figure 3. Notched Specimen

BOLTED JOINT STRENGTH ANALYSIS

Strength analysis for composite bolted joints
involves the mating of a stress analysis with an appropriate
mode specific failure criterion for each of the primary
failure modes. The stress analysis and failure criteria are
independent of each other, and can be manipulated separately
in order to optimize the strength analysis package formed by
by their coupling. Two methods of stress analysis were
proposed, an approximate elasticity plane-stress formulation,
and finite element analysis. The objective is to determine
the simplest effective stress analysis which provides
reliable results in combination with the empirically based
failure criteria.

Both two-dimensional plane stress and pseudo three-
dimensional finite element analyses were proposed. In order
to more fully understand the bearing failure mechanism, a
full three-dimensional finite element analysis has been
substituted for the pseudo three-dimensional analysis. Both
the 2-D and 3-D elements employ orthotropic material
properties.

The mesh has been developed for the two-dimensional
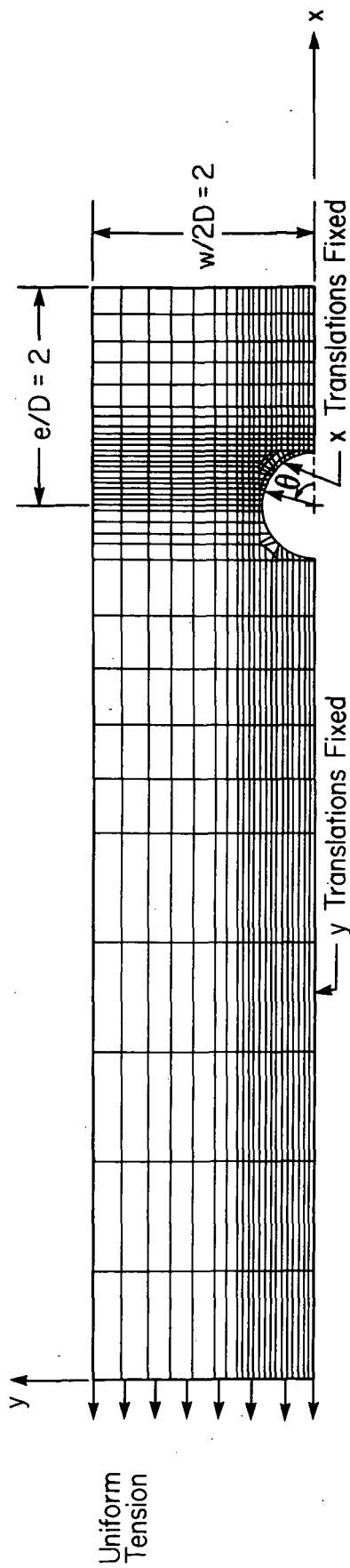plane stress analysis and is shown in Figure 4. Mechanical

Figure 4.   Finite Element Model Used to Analyze the Bolted Joint.

loads are applied axially along the x=0 edge, and the bolt
is simulated by fixing the x translations of the nodes along
the hole boundary, excluding the two nodes near the 90°
position. Symmetry was used to reduce the number of degrees
of freedom necessary for solution of the problem. The mesh
and boundary conditions are a refinement of those employed
for previous bolted joint studies [14-15], and have been
shown to provide accurate results for stresses along the net
tension and shearout planes.

The three-dimensional finite element analysis will
employ the same mesh, only contain elements through the
thickness. The inplane boundary conditions remain similar.
A compressive uniform pressure distribution will be employed
to model constraint by the washer and the transverse
compressive loads introduced by torque on the bolt. This
analysis will only be used for a limited number of case
studies directed at characterizing the bearing failure
mechanism.

A literature survey has identified several approximate
elasticity solutions [1,2,4,16,17] for composite bolted
joint stress analysis. The solutions all treat the laminate
as a homogeneous orthotropic plate of infinite width loaded
by a rigid circular inclusion. A solution also exists for
the case of an infinite orthotropic plate containing a

circular cutout loaded in tension. The superposition of
these two solutions allows the analysis of bolt-bearing
bypass loading conditions, such as experienced when rows of
fasteners are employed.

Finite width correction factors must be employed to
these analyses to account for fastener interactions or
interactions between the fastener and edge of the plate. In
addition, the loading induced by the fastener is assumed to
be a cosine distribution, an assumption which breaks down
for some combinations of geometry and anisotropy. Even with
these limitations, the accuracy has been deemed satisfactory
enough to base several bolted joint analysis packages on this
form of stress analysis [1,2,10].

A version of Waszczak's solution, which uses anisotropic
elasticity theory, has been developed and programmed into the
the computer to form a stress analysis module. In this
solution, the complex stress function

$$F(x,y) = 2R_e [F_1(z_1) + F_2(z_2)]$$

is used to express the components of stress as follows:

$$\sigma_x = \partial^2 F / \partial y^2$$

$$\sigma_y = \partial^2 F / \partial x^2$$

$$\tau_{xy} = \partial^2 F / \partial x \partial y$$

The complex stress functions are analytic functions of the complex characteristic coordinates z_1 and z_2, where

$$z_1 = x + \mu_1 y$$

$$z_2 = x + \mu_2 y$$

and should not be confused with the complex physical coordinates z which are given by

$$z = x + iy$$

Compatibility requires that the following characteristic equation be satisfied by the μ_k values.

$$B_{ij}\mu^4 - 2B_{16}\mu^3 + (2B_{12} + B_{66})\mu^2 - 2B_{26}\mu + B_{22} = 0$$

Thus, the μ_k are found in terms of the material compliance, B_{ij}. For an anisotropic material, four distinct roots are obtained. A mapping function is employed to map the internal boundary of the fastener hole into a unit circle in the transformed plane. The mapping function is

$$\zeta_k = \frac{z_k \pm \sqrt{z^2 - a^2 - \mu_k^2 a^2}}{a(1 - i\mu_k)}$$

where only one of the two values of ζ_k lies inside the unit

circle, the other maps to a point outside the unit circle. The point outside the unit circle is the one of interest.

Making the following simplification in notation by letting

$$\phi_1(z_1) = dF_1(z_1)/dz_1$$

$$\phi_2(z_2) = dF_2(z_2)/dz_2$$

the stress components become

$$\sigma_x = 2\,\text{Re}\,[u_1^2\phi_1'(z_1) + u_2^2\phi_2'(z_2)]$$

$$\sigma_y = 2\,\text{Re}\,[\phi_1'(z_1) + \phi_2'(z_2)$$

$$\tau_{xy} = 2\,\text{Re}\,[u_1\phi_1'(z_1) + u_2\phi_2'(z_2)$$

Because of the mapping function, the dimensionality of the problem has been reduced by one, and the boundary conditions can be introduced by a complex Fourier series in terms of the single variable θ .

Requiring that all stress components be real and single valued, the function ϕ_k for a loaded hole in an infinite plate has been shown to be of the following form.

$$\phi_k(\zeta_k) = A_k/u_k\zeta_k + \sum_{m=1}^{\infty} A_{km}\zeta_k^{-m} \qquad k = 1,2$$

By applying the boundary conditions and imposing the equilibrium conditions, the constants A_k and A_{km} can be determined for a known load. Once the ϕ_k is known, the stress components can be determined.

The computer code developed to perform this stress analysis is currently being verified and debugged.

FAILURE CRITERIA

Ideally, the failure criterion should use a basic material property to predict failure of the composite laminate. For the case of unidirectional continuous fiber based laminates, the basic material properties are failure stresses and/or strains of a single ply in the principal directions (normally x_1^T, x_1^C, x_2^T, x_2^C, s^6, etc.). When the laminate consists of a combination of unidirectional and off-axis ply orientations, the failure of each ply will depend upon its orientation with respect to the principal loading axis. Most failure criteria perform a ply-by-ply analysis and designate first ply failure as failure of the laminate. The drawbacks to that philosophy are obvious if one considers a laminate with 90° plies. The inaccuracy of the first ply failure analysis has been circumvented by many investigators by using progressive-failure analysis; that is, redistributing the load upon ply failure and continuing until ultimate failure occurs.

Another option has been to use laminate based failure parameters instead of ply properties. The result is better accuracy, but more data must be collected since each laminate configuration demands a new set of data. However,

even this type of failure criterion is far less data intensive
than bolted joint characterization.

Woven fabrics do not exhibit strong differences in
strength as a function of direction, like unidirectional
systems. Therefore, the first ply failure problem should be
less of a factor in laminate failure prediction. Woven
fabrics are not as anisotropic in properties as unidirectional
tape composites, making the first ply failure less significant
in laminate strength analysis. In view of these considerations,
both ply-by-ply and laminate based failure criteria will be
evaluated.

Candidate failure criteria have been identified for
each failure mode based on current knowledge of bolted joint
failure mechanisms. Comparisons of more than one criteria
will be made in cases where appropriate. The criteria
which will be investigated for each failure mode are listed
below.

```
Net Tension:   Point Stress Criterion
               Quadratic Interaction Criterion

Shearout:      Point Stress Criterion
               Quadratic Interaction Criterion

Bearing:       Collings Criterion
               Quadratic Interaction Criterion
               (full 3-D)
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The essence of the point stress criterion can be stated mathematically as follows:

$$\sigma_i \big|_{x=r+d_o} = \sigma_o$$

where σ_i = stress component adjacent to the hole for the failure mode under consideration

σ_o = unnotched strength of the laminate for the failure mode under consideration

d_o = is the critical distance parameter

The critical distance parameter is a function of hole size and has the following form [22].

$$d_o = \frac{1}{c}\left(\frac{R}{R_o}\right)^m$$

Constants c and m are found from empirical data by determining d_o for two notch sizes under bolted joint loading conditions.

The quadratic interaction criterion is expressed in the following form to predict strength of composites subjected to multiaxial states of stress.

$$F_i\sigma_i + F_{ij}\sigma_i\sigma_j \geq 1 \qquad\qquad i = 1,3$$

where the F_i and F_{ij} are strength tensors of 2nd and 4th rank, and the σ_i are the stress components. The strength tensors must be determined from experiment for each material system

considered. Failure occurs when the sum of the tensor products exceeds unity.

The bearing failure criterion developed by Collings [6] was based on careful observation of bearing and compression failures of laminates. Collings determines the average bearing stresses in basic subunits of the laminate such as:

$$\sigma_{b_1} = \frac{1}{A}(\sigma_o A_o + \sigma_{b_{45}} A_{45}) \qquad \text{for a } 0/\pm45 \text{ sublaminate}$$

$$\sigma_{b_2} = \frac{1}{A}(\sigma_{90} A_{90} + \sigma_{b_{45}} A_{45}) \qquad \text{for a } 90/\pm45 \text{ sublaminate}$$

$$\sigma_{b_3} = \frac{1}{A}(\sigma_{b_o} A_o + \sigma_{90} A_{90}) \qquad \text{for a } 0/90 \text{ sublaminate}$$

where σ_o is the average bearing stress in 0° plies at failure

σ_{90} is the average bearing stress in the 90° plies at failure

$\sigma_{b_{45}}$ is the average bearing strength of a ±45° laminate

σ_{b_o} is the average bearing strength of a 0° laminate

A_o , A_{90} , A_{45} are the projected areas of the 0°, 90° and ±45° plies, respectively

The interaction effects (resulting from the presence of other plies) on bearing strength of 0° and 90° plies in multidirectional laminates expressed through ply bearing factors.

These factors are defined as

$$k_o = \frac{\sigma_c}{\sigma_o}$$

and

$$k_{90} = \frac{\sigma_{TC}}{\sigma_{90}}$$

where σ_c is the longitudinal compression strength

σ_{TC} is the constrained transverse compression strength

Using these bearing factors in conjunction with the preceding equations for bearing stresses, bearing strength expressions are formed.

For 0/±45 laminates

$$\sigma_{b_1} = \frac{1}{t}[\frac{t_o \sigma_c}{k_o} + t_{45} \sigma_{b_{45}}]$$

for 90/±45 laminates

$$\sigma_{b_2} = \frac{1}{t}[\frac{t_{90} \sigma_{TC}}{k_{90}} + t_{45} \sigma_{b_{45}}]$$

and for 0/90 laminates

$$\sigma_{b_3} = \frac{1}{t}[\frac{t_{90} \sigma_{TC}}{k_{90}} + t_o \sigma_{b_o}]$$

When laminates contain more than three fiber directions, the above criteria can be superposed to give the bearing strength of the new laminate.

These failure criteria have all been used with varying degrees of success in composite bolted joint strength analysis. From the present research, their applicability to woven fabric composites will be assessed. The most accurate criteria for each failure mode will be incorporated into a bolted joint failure analysis package.

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