

ARMY RESEARCH LABORATORY



Effect of an Angle-Ply Orientation on Compression Strength of Composite Laminates

by Christopher P. R. Hoppel
and Steven J. De Teresa

ARL-TR-2003

June 1999

Approved for public release; distribution is unlimited.

DTIC QUALITY INSPECTED 4

19990913 109

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

Army Research Laboratory

Aberdeen Proving Ground, MD 21005-5069

ARL-TR-2003

June 1999

Effect of an Angle-Ply Orientation on Compression Strength of Composite Laminates

Christopher P. R. Hoppel

Weapons and Materials Research Directorate, ARL

Steven J. De Teresa

Lawrence Livermore National Laboratory

Abstract

An experimental program was initiated to investigate the effect of angle-ply orientations on the compressive strength (X1C) of 0° plies in fiber-reinforced composite laminates. Graphite fiber-reinforced epoxy test coupons with the generic architecture $[0_2/\pm\theta]$ (where θ varied between 0° and 90°) and for the quasi-isotropic architecture were evaluated. The effective compressive strength of the 0° plies varied considerably. The results were related to the Poisson's ratios of the laminates, with high Poisson's ratios leading to high transverse tensile strains in the test coupons and lower-than-expected strengths. Specimens with the $[0_2/\pm30]$ architecture had both the highest Poisson's ratio and the lowest calculated ply-level compression strength for the 0° plies.

This work has implications in the selection of composite failure criteria for compression performance, design of test coupons for acceptance testing and the selection of laminate architectures for optimum combinations of compressive and shear behavior. Two commonly used composite failure criteria, the maximum stress and the Tsai-Wu, predict significantly different laminate strengths depending on the Poisson's ratio of the laminate. This implies that the biaxial stress state in the laminate needs to be carefully considered before backing out unidirectional properties.

Table of Contents

	<u>Page</u>
List of Figures	v
List of Tables	vii
1. Introduction	1
2. Analysis	2
3. Experimental	6
4. Results	9
5. Discussion	12
6. Conclusions	14
7. References	15
Distribution List	17
Report Documentation Page	29

INTENTIONALLY LEFT BLANK.

List of Figures

<u>Figure</u>	<u>Page</u>
1. Effect of ply architecture on laminate strength for a series of laminates with the generic architecture $[\theta/0/-\theta/0]_{2S}$ (θ varies between 0° and 90°) and for the quasi-isotropic architecture $[45/90/-45/0]_{2S}$	4
2. Effect of ply architecture on ν_{12} for a series of laminates with $[\theta/0-\theta/0]_{2S}$ (θ varies between 0° and 90°) and for the quasi-isotropic architectures	5
3. Transverse stresses in the 0° ply at failure (based on the maximum stress failure criterion) for a series of laminates with the generic architecture $[\theta/0/-\theta/0]_{2S}$ (θ varies between 0° and 90°) and for the quasi-isotropic architecture $[45/90/-45/0]_{2S}$	6
4. Schematic of tabbed compression specimen and fixture	7
5. Failed specimens of ± 60 , quasi-isotropic, and unidirectional laminates	11
6. Failed specimens of $[30/0/-30/0]_{2S}$ laminates	11
7. Backed-out compressive strengths for the $[\theta/0/-\theta/0]_{2S}$ and quasi-isotropic laminates	12

INTENTIONALLY LEFT BLANK.

List of Tables

<u>Table</u>		<u>Page</u>
1.	Lamina Elastic Constants for IM7/8551-7 (Jiang and Tennyson 1989)	3
2.	Lamina Failure Constants for IM7/8551-7 (Jiang and Tennyson 1989)	3
3.	Results of Laminate Compressive Tests and Backed-Out 0° Strengths	10

INTENTIONALLY LEFT BLANK.

1. Introduction

Angle-ply or axially biased composite laminates are an important class of laminates because they combine good properties in the axial and shear directions. The Army has been interested in these laminates for a variety of ballistic applications. However, the $[30/0/-30/0]_{2s}$ architecture, which offered one of the best combinations of axial and shear properties, had a much lower experimental compressive strength than that predicted using the maximum stress or maximum strain failure criteria. The present investigation was initiated to evaluate the cause of this low compressive strength and to evaluate the suitability of several failure criteria for predicting laminate compressive strength.

Compression testing of composite laminates is important for establishing failure limits as well as material quality control. However, compression test results can vary significantly depending on the test method and the architecture of the laminate being tested (Camponeschi 1991). In general, unidirectional laminates give low compressive strengths due to instability during failure. There has been significant interest (Camponeschi and Hoyns 1991; Wilson et al. 1994; Welsh and Adams 1996 and 1997) in testing angle-ply or cross-ply composite laminates and "backing-out" the unidirectional strength of the material. The use of the back-out factor to calculate unidirectional strength assumes that the compressive failure is controlled by the axial stress state in the 0° ply.

Several investigators have evaluated the use of angle-ply laminates to determine 0° compressive strength. Anquez (1994) proposed that the biaxial stress state in the composite laminates is important for evaluating compressive strengths. That work also proposed that optimum strength values could be obtained by backing out the 0° strength from a $0_2/\pm 60$ laminate, which has the same Poisson's ratio as a unidirectional laminate. Welsh and Adams (1997) reached a similar conclusion after evaluating angle-ply laminates to obtain compressive strength.

In the present study, the effect of material architecture on the compressive strength is evaluated. Experimental results are given for a range of angle-ply laminates, and the

backed-out unidirectional strengths are discussed in light of the biaxial stress state within the composite laminates. The IM7/8551-7 graphite fiber-reinforced epoxy material system is used for this evaluation. This material is of interest because it is used in a variety of Army applications.

2. Analysis

A variety of failure criteria exists for composite materials (Nahas 1986). Some of the most common are the maximum stress, the maximum strain, and the Tsai-Wu (Tsai 1987; Tsai and Wu 1971). Of these, the maximum stress failure criterion does not account for any interaction between the stresses in the laminate but does identify the operative failure modes in the laminate. The maximum strain failure criterion provides some interaction between the stresses (due to Poisson's effects) and also identifies the operative failure modes. The Tsai-Wu or tensor-polynomial criterion provides interaction between the stresses in the laminate but does not identify the specific failure mode. The Tsai-Wu equation is given in Equation 1, and the coefficients F_{ij} are listed in Equations 2 through 7. Two other failure criteria, proposed by Hashin (1980) and Christensen (1988), differentiate between fiber and matrix failure modes. For the fiber-dominant failure mode, both of these failure criteria are similar to the maximum strain criterion.

$$F_1\sigma_1 + F_2(\sigma_2 + \sigma_3) + F_{11}\sigma_1^2 + F_{22}(\sigma_2^2 + \sigma_3^2) + 2F_{12}\sigma_1(\sigma_2 + \sigma_3) + 2F_{23}\sigma_2\sigma_3 + F_{44}\sigma_4^2 + F_{66}(\sigma_5^2 + \sigma_6^2) = 1 \quad (1)$$

$$F_1 = \frac{1}{X1T} - \frac{1}{X1C} \quad (2)$$

$$F_2 = \frac{1}{X2T} - \frac{1}{X2C} \quad (3)$$

$$F_{11} = \frac{1}{(X1T)(X1C)} \quad (4)$$

$$F_{22} = \frac{1}{(X2T)(X2C)} \quad (5)$$

$$F_{44} = 2(F_{22} - F_{23}) \quad (6)$$

$$F_{66} = \frac{1}{S_6^2} \quad (7)$$

Jiang and Tennyson (1989) evaluated the elastic constants and failure allowables for the IM7/8551-7 material system in the principal directions. The results of their work are listed in Table 1 and Table 2. For the Tsai-Wu failure criterion, Hahn and Kallas (1992) determined the two interaction terms that require biaxial testing: F_{12} was reported as $4.001 \times 10^{-11} \text{ ksi}^{-2}$ ($8.412 \times 10^{-7} \text{ MPa}^{-2}$), and F_{23} was reported as $6.1698 \times 10^{-10} \text{ ksi}^{-2}$ ($1.2972 \times 10^{-5} \text{ MPa}^{-2}$).

Table 1. Lamina Elastic Constants for IM7/8551-7 (Jiang and Tennyson 1989)

Elastic Property	Value (English Units)	Value (Metric Units)
E_{11}	23.5 msi	162 GPa
E_{22}	1.21 msi	8.34 GPa
G_{12}	0.69 msi	4.79 GPa
ν_{12}	0.339	0.339

Table 2. Lamina Failure Constants for IM7/8551-7 (Jiang and Tennyson 1989)

Direction	Strength (English Units)	Strength (Metric Units)
X1T	351	2417
X1C	150	1035
X2T	11	73
X2C	26	176
S12	27	183

Using the data reported by Jiang and Tennyson (1989) and Hahn and Kallas (1992), the predicted strengths were calculated for a series of angle-ply laminates using four different failure criteria. The strengths were calculated using LAM3D software (Bogetti, Hoppel, and Drysdale 1995), which uses a "smearing-unsmeared" theory (Chou, Carleone, and Hsu 1972) to calculate ply-level stresses in a laminate and apply a failure criterion to

each ply. The laminates had the generic form $[\theta/0/-\theta/0]_{2S}$ (with θ varying between 0° and 90°) and for the quasi-isotropic architecture $[45/90/-45/0]_{2S}$. The predictions do not include thermal stresses due to manufacturing the laminate or edge effects in the test specimens. The results are shown in Figure 1. LAM3D was also used to calculate the laminate Poisson's ratios as well as the ply-level stress states at failure.

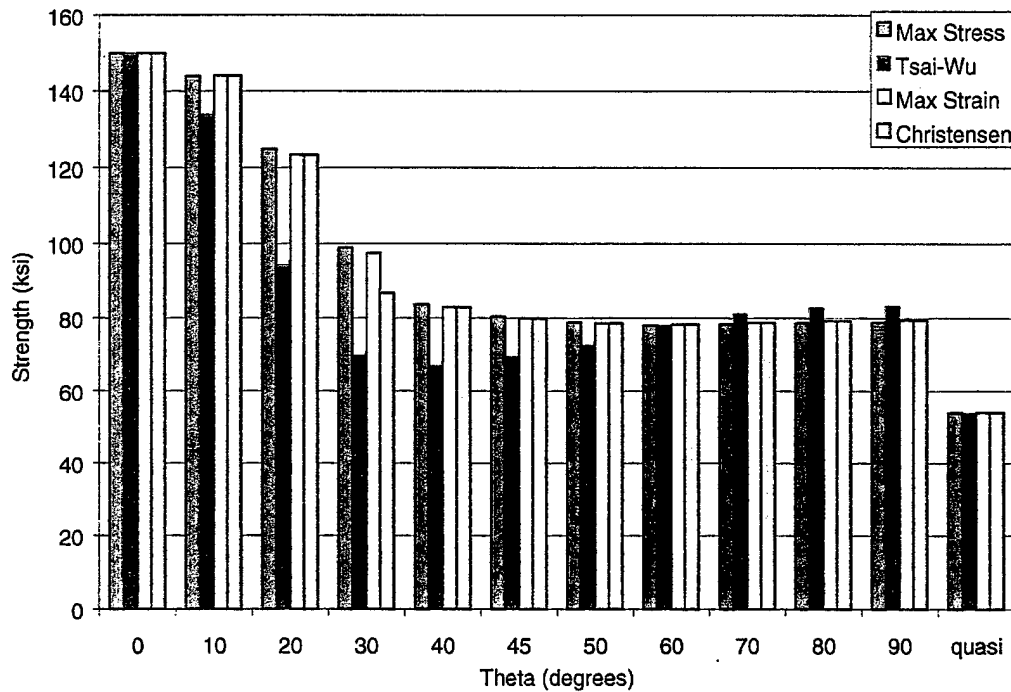


Figure 1. Effect of ply architecture on laminate strength for a series of laminates with the generic architecture $[\theta/0/-\theta/0]_{2S}$ (θ varies between 0° and 90°) and for the quasi-isotropic architecture $[45/90/-45/0]_{2S}$.

From Figure 1, the four failure criteria show similar strength predictions when θ equals 0° or 60° and for the quasi-isotropic architecture; however, for other values of θ , the predictions differ significantly. The main reason for these differences is the biaxial stress state in the 0° ply for each of the architectures.

The Poisson's ratios are shown in Figure 2. The $[60/0/-60/0]_{2S}$ and $[45/90/-45/0]_{2S}$ architectures both have Poisson's ratios close to that of the unidirectional laminate. For values of θ between 0° and 60° , the Poisson's ratio is much greater than that of the unidirectional lamina; the maximum Poisson's ratio is for the $[30/0/-30/0]_{2S}$

architecture. When the Poisson's ratios are greater than those of the unidirectional laminate, the 0° plies are placed in transverse tension when the laminate is loaded in compression. The transverse tensile stresses in the 0° plies in the center of the laminate at failure (based on the maximum stress failure criterion) were calculated using LAM3D and are plotted in Figure 3. The $[30/0/-30/0]_{2s}$ laminate shows transverse tensile loads close to the maximum allowable (Table 2). The transverse stresses are compressive for values of θ greater than 60° . These compressive stresses may add stability to the laminate and delay the axial compressive failure.

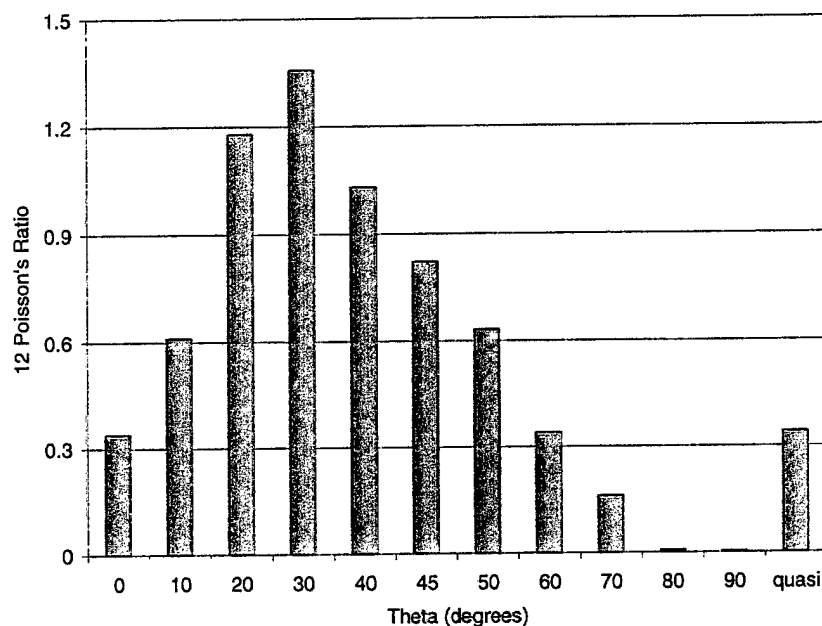


Figure 2. Effect of ply architecture on ν_{12} for a series of laminates with $[\theta/0/-\theta/0]_{2s}$ (θ varies between 0° and 90°) and for the quasi-isotropic architectures.

The interactive failure criteria show significant effects due to the transverse stress state. The Tsai-Wu failure criterion predicts lower laminate strengths than the other failure criteria for laminates with high Poisson's ratios. For laminates with low Poisson's ratios, the Tsai-Wu criterion predicts higher strengths. The maximum strain and Christensen's failure criteria both predict laminate strengths similar to the maximum stress failure criterion, with the only exception being the prediction for the $[30/0/-30/0]_{2s}$ using Christensen's failure criterion. For this laminate, Christensen's criterion predicts a matrix dominated failure mode and a lower strength than the maximum stress or maximum strain.

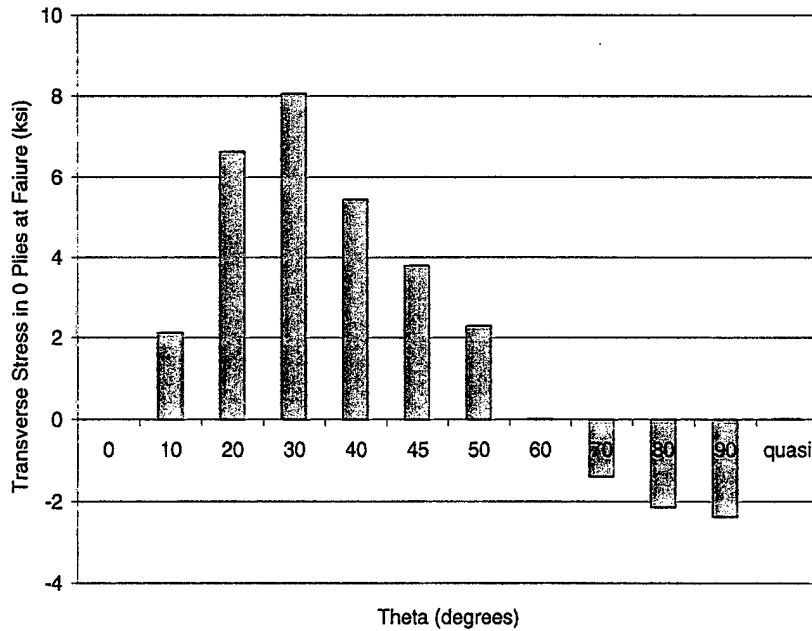


Figure 3. Transverse stresses in the 0° ply at failure (based on the maximum stress failure criterion) for a series of laminates with the generic architecture $[\theta/0/-\theta/0]_{2S}$ (θ varies between 0° and 90°) and for the quasi-isotropic architecture $[45/90/-45/0]_{2S}$. The transverse stresses are tensile for values of θ between 0° and 60°, compressive for values of θ between 60° and 90°, and close to 0 for the 0° $[60/0/-60/0]_{2S}$ and quasi-isotropic architectures.

3. Experimental

A series of laminates from the family $[\theta/0/-\theta/0]_{2S}$ with $\theta = 0^\circ, 30^\circ, 45^\circ, 60^\circ,$ and 90° were made from IM7/8551-7 unidirectional prepreg. A laminate made from the widely used $[45/90/-45/0]_{2S}$ quasi-isotropic layup was also fabricated. Square 12-in panels were autoclave cured following the manufacturer's recommended layup procedure and cure cycle. Cured panels were examined using ultrasonic C-scans and were found to be free of any gross porosity or delaminations. The average thickness of the cured ply was 0.0056 in.

All compression tests were conducted using a variant of the Boeing-modified ASTM D695 specimen. These were 0.5-in-wide x 3.2-in-long strips of composite with either fiberglass or carbon fiber composite tabs adhesively bonded at each end to form a gauge length of 0.4 in. Carbon fiber tabs were used for the unidirectional specimens after it was

found that the weaker fiberglass would prematurely fail at the ends. The specimen is shown in Figure 4. It was selected because of its widespread use and compact size. Modifications to the standard specimen were made following the work by Haberle and Matthews (1994). Their work has shown that improved unidirectional strengths and reduced scatter are obtained when the high shear stresses near the tab end are relieved by eliminating the adhesive bond in this area. This unbonded area is made in a controlled manner by covering an area slightly greater than the gauge section of the specimen with a release-coated tape prior to bonding the tabs. In the present study, the stress-relief preparation was used for both uni- and multidirectional laminates. For comparison, a set of unidirectional specimens was prepared without the release tape to give fully bonded tabs.

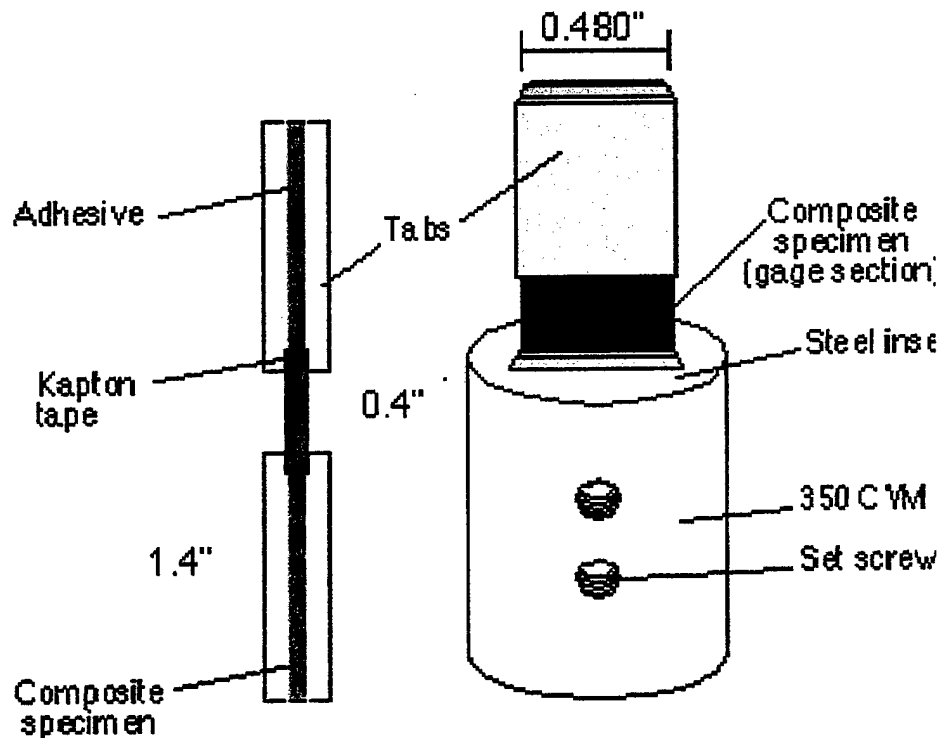


Figure 4. Schematic of tabbed compression specimen and fixture.

Specimens were prepared from 6-in x 3.5-in composite plates that were cut from the panels using a diamond saw under flood coolant. The gauge area was covered with $\frac{3}{4}$ -in-wide Kapton tape that had a release backing. With this width tape, the final specimens have an intentional 0.18-in unbonded length at the tab ends. The bonding surfaces were lightly

abraded, then cleaned with acetone and isopropanol. Tabs 6 in long by 1.5 in wide were bonded to the composite using a 0.010-in-thick film adhesive (3M AF-126-2). An aluminum alignment fixture was used during the adhesive cure to maintain the position of the tabs. The adhesive was cured in a press under 50-psi pressure for 1.0 hr at 250° F. Shims were used in the alignment fixture to yield an adhesive bondline that was nominally 0.005 in thick.

All four edges of the tabbed panel were trimmed with the diamond saw using a previously marked panel edge for reference. The ends and the surfaces of the tabs were then ground flat and parallel under flood coolant using a surface grinder. After grinding, the panel was sectioned into 0.5-in-wide specimens using the diamond saw and then ground to 0.480-in widths using the surface grinder.

The compression test fixture shown schematically in Figure 4 is also based on some of the work due to Haberle and Matthews (1994). Like their design, ours utilizes two independent fixtures (only one is shown in the figure) and is thus free of any of the friction forces that are present in the standard D695 fixture. The ends of the specimen are fully contained in the fixture, which reduces the chance of end failures. It is designed for use in a high-pressure vessel for study of the effects of superimposed pressure on the failure of fiber composites. The two fixtures were machined from annealed 350 CVM maraging steel with precision rectangular holes. The holes are 0.380 in thick and 0.500 in wide, which leaves room for lateral Poisson's expansion of the 0.480-in-wide specimens. This expansion is significant in the ± 30 and ± 45 laminates and could lead to premature failure if constrained by the fixture. The thickness of the hole was designed to accommodate different tabbed specimens while leaving space for the steel insert as shown in the figure. A "grip" compression is applied to the tabs through the steel insert via two setscrews on the side of the fixture. This force has been shown beneficial in preventing premature tab failures in compression tests (Haberle and Matthews 1994). Shims were used to center the 0.480-in-wide specimen in the 0.500-in-wide slots of the fixtures. These shims were left in place until after the setscrews were tightened to a torque of 50 in-lb. The alignment between the two fixtures is maintained by inserting the whole assembly inside a precisely bored guide

tube. All tests were conducted at a stroke rate of 0.05 in/min using an MTS servo-hydraulic test machine.

4. Results

The results of the laminate compression tests are listed in Table 3. Figure 5 gives some examples of failure in the ± 60 , quasi-isotropic, and unidirectional laminates. The failure surfaces of most of the laminates were shear-type fractures, oriented at about 70° with respect to the load direction (the 0° direction) or a brooming-type failure. These fractures were confined to the gauge section with many appearing to have occurred at one tab end. Both the stress-relieved and fully bonded unidirectional specimens also appeared to have failed at one end of the gauge section. Despite this similarity, there was a noticeable improvement in strength for the specimens that were stress-relieved. This result is similar to the findings of Haberle and Matthews (1994). The average strength of the stress-relieved unidirectional specimen was 231 ksi. For comparison, manufacturer's data for this composite system claim a unidirectional compression strength in the range 243–252 ksi (Hercules Aerospace Products Group 1985), significantly higher than the results reported by Jiang and Tennyson (1989).

In contrast, the ± 30 laminates failed almost cleanly along one of the 30° directions, leaving the fibers in the opposing 30° plies and the 0° plies completely severed, indicating a different failure mode than the other specimens. Examples of this failure mode are shown in Figure 6. The failure propagated well into the tab area but appeared to have initiated in the gauge section near the tab.

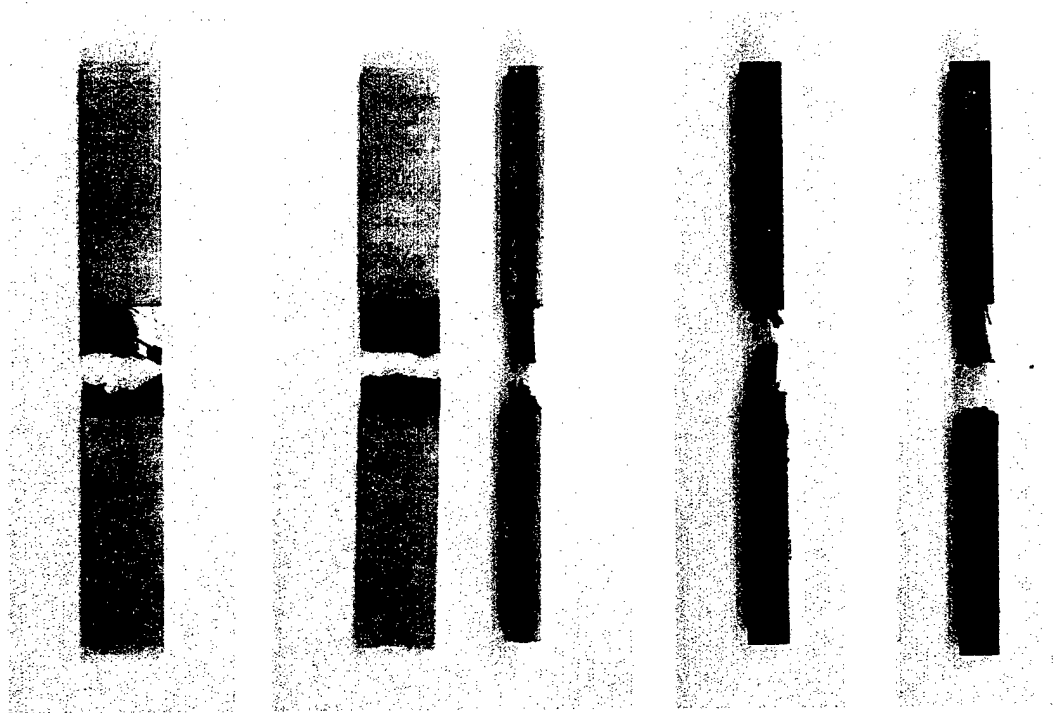
The 0° strengths were backed-out of the experimental laminate strengths using two different methods. The maximum stress failure criterion method is the same as the back-out factor used in other studies (Camponeschi and Hoyns 1991). The backed Tsai-Wu strength was found by solving equations 1 through 7 for X1C (the lamina compressive strength), assuming $\sigma_3 = \sigma_4 = \sigma_5 = \sigma_6 = 0$. This approximation was made based on the macroscopic stress-state predicted with LAM3D software. LAM3D uses a "smearing" methodology to model global laminate properties but does not model the intra-ply stresses. The backed-out

strengths are shown in Figure 7. The Tsai-Wu equation solved for X1C is given in equation 8:

$$X1C = \frac{\frac{\sigma_1^2}{X1T} - \sigma_1}{1 - \frac{\sigma_1}{X1T} - \sigma_2 \left(\frac{1}{X2T} - \frac{1}{X2C} \right) - \frac{\sigma_2^2}{(X2T)(X2C)} - 2F_{12}\sigma_1\sigma_2} \quad (8)$$

Table 3. Results of Laminate Compressive Tests and Backed-Out 0° Strengths

Laminate	Compressive Strength (ksi)	Standard Deviation (ksi)	Backed-Out 0° Strength (ksi)	Backed-Out 0° Strength Based on Tsai-Wu (ksi)
[0] ₁₆ (no stress relief)	211	3.3	211	211
[0] ₁₆ (stress relieved)	231	2.8	231	231
[30/0/-30/0] _{2S}	146	0.1	222	242
[45/0/-45/0] _{2S}	150	2.3	281	317
[60/0/-60/0] _{2S}	134	1.3	257	258
[90/0] _{4S}	146	8.1	277	236
[45/90/-45/0] _{2S}	96	6.5	267	267



$[60/0/-60/0]_{2s}$ $[45/90/-45/0]_{2s}$ $[0]_{16}$ (Tape) $[0]_{16}$ (No Tape)

Figure 5. Failed specimens of ± 60 , quasi-isotropic, and unidirectional laminates.



Figure 6. Failed specimens of $[30/0/-30/0]_{2s}$ laminates.

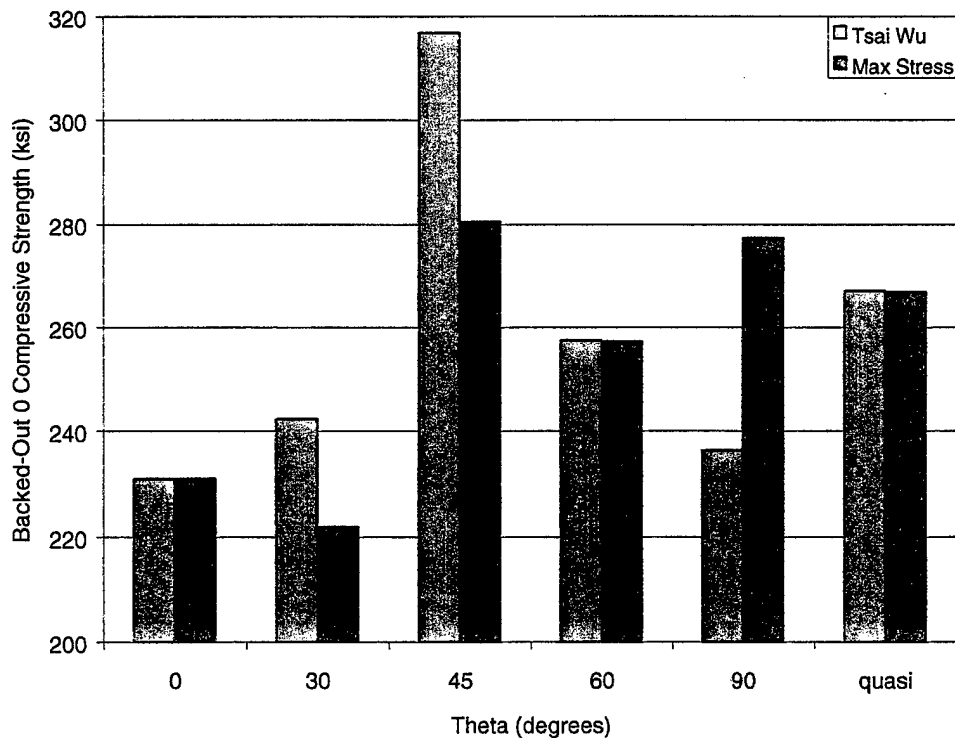


Figure 7. Backed-out compressive strengths for the $[\theta/0/-\theta/0]_{2s}$ and quasi-isotropic laminates.

5. Discussion

From the results in Table 3 and Figure 7, it can be seen that the backed-out unidirectional strengths for composite laminates can differ significantly depending on the laminate architecture as well as the method used to back out the strength. Using the Tsai-Wu failure criterion to back out the unidirectional strength as was done here is probably inappropriate for most applications because it assumes failure is dominated by the 0° axial compressive strength (whereas the Tsai-Wu failure criterion assumes failure is due to the multiaxial stress-state). However, it was done in this paper to illustrate the importance of the biaxial stress state in the failure of the laminate. For angle-ply laminates with Poisson's ratios greater than the unidirectional lamina, the tensile transverse stresses in the 0° plies may contribute to lower axial compressive strengths than in other architectures. Likewise, for cross-ply laminates, the compressive transverse stresses that develop in the 0° plies may contribute to higher axial compressive strengths than in other architectures. In either case,

backing out the unidirectional strength from these laminates using the maximum stress failure criterion ignores the biaxial stress state and can create misleading results. The laminates with the same Poisson's ratios as the unidirectional lamina (such as $[60/0/-60/0]_{2s}$ or $[45/90/-45/0]_{2s}$) remove the biaxial stress state and are more appropriate for backing out the unidirectional strengths. In the present analysis, these architectures gave the same backed out strengths for either maximum stress or Tsai-Wu back out factors.

It should be noted that all of the compressive strengths measured and calculated in this study were significantly higher than the 150-ksi compressive strength originally reported by Jiang and Tennyson (1989) and used for the comparison in Figure 1. This demonstrates that differences in compressive test methods can also significantly affect strength predictions. The laminate compressive strengths were recalculated using the 231-ksi unidirectional strength found in this study, and the laminate strengths increased proportionally. One significant difference occurred: for the $[30/0/-30/0]_{2s}$ laminate with the 231-ksi unidirectional axial strength, the maximum stress and maximum strain failure criteria predicted a transverse tensile failure mode, which is supported by the difference in failure mode seen in this study.

It should also be noted that the "backed-out" Tsai-Wu strengths calculated from equation 8 use the other failure constants from Jiang and Tennyson as listed in Table 2. Since these constants all have some variability, it adds to the total variability of the backed-out Tsai-Wu strengths.

As discussed in the introduction, there are two main reasons for compression testing composite laminates: establishing failure limits and material quality control. The main focus of this paper has been the risks associated with backing unidirectional strengths out of angle-ply laminates for establishing failure limits. While the authors do not recommend using a Tsai-Wu backed-out strength as was done here, it illustrates the importance of the biaxial stress state in compressive failure. This method of backing out unidirectional strengths may prove to be an effective method for comparing different failure criteria. A

measure of the success of a particular failure criterion may be how consistently the same unidirectional strength can be backed-out for different laminates.

6. Conclusions

The influence of architecture on the compressive behavior of angle-ply composite laminates is evaluated. The analytic predictions and experimental results presented in this paper both show that the biaxial stress state that develops in angle-ply composite laminates has a significant effect on the axial compressive strength. Laminates with high Poisson's ratios, such as the $[30/0/-30/0]_{2s}$, produce transverse tensile strains when they are loaded in axial compression and consequently have lower strengths than predicted using a maximum stress-type failure criterion. Similarly, laminates with low Poisson's ratio, such as the $[90/0]_{4s}$, produce transverse compressive strains when they are loaded in compression and may give artificially high estimates of the unidirectional compressive strengths.

This work has implications in the selection of composite failure criterion for compression performance, design of test coupons for acceptance testing, and the selection of laminate architectures for optimum combinations of compressive and shear behavior. Two commonly used composite failure criteria, the maximum stress and the Tsai-Wu, predict significantly different lamina strengths depending on the Poisson's ratio of the laminate. Compressive strength is ultimately dependent on the materials, architecture, loading conditions, and structural geometry. At this point, the best way to evaluate the strength of composite structures is to test those structures in the architectures and loading state that they will experience. When this is not possible, the designer needs to acknowledge the uncertainties in their backed-out stress and increase their factor of safety accordingly.

7. References

- Anquez, L. "Experimental Investigations to Assess Typical Compressive Behavior of Composites." *Proceedings of the 30th Polymer Matrix Composites Coordination Group Meeting (MIL-HDBK-17)*. New Orleans, LA, pp. 139-146, 1994.
- Bogetti T. A., C. P. R. Hoppel, and B. P. Burns. "LAMPAT: A Software Tool for Analyzing and Designing Thick Laminated Composite Structures." ARL-TR-890, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, September 1995.
- Bogetti, T. A., C. P. R. Hoppel, and W. H. Drysdale. "Three-Dimensional Effective Property and Strength Prediction of Thick Laminated Composite Media." ARL-TR-911, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, October 1995.
- Camponeschi, E. T., "Compression of Composite Materials: A Review." *Composite Materials: Fatigue and Fracture (Third Volume)*. ASTM STP 1110, T. K. O'Brien, Ed., American Society for Testing and Materials, Philadelphia, PA, pp. 550-578, 1991.
- Camponeschi E. T., and D. Hoyns. "Determination of Effective [0] Properties From [0/90] Laminate Testing." *ASTM D30.04 Spring 1991 Meeting*. American Society for Testing and Materials, Philadelphia, PA, 1991.
- Chou, P. C., J. Carleone, and C. M. Hsu. "Elastic Constants of Layered Media." *Journal of Composite Materials*, vol. 6, pp. 80-93, 1972.
- Christensen, R. M. "Tensor Transformations and Failure Criteria for the Analysis of Fiber Composite Materials." *Journal of Composite Materials*, vol. 22, pp. 874-897, 1988.
- Haberle, J. G. and F. L. Matthews, "An Improved Technique for Compression Testing of Unidirectional Fibre-Reinforced Plastics; Development and Results." *Composites*, vol. 25, no. 5, pp. 358-371, 1994.
- Hahn, H. T., and M. N. Kallas. "Failure Criteria for Thick Composites." BRL-CR-691, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, June 1992.
- Hashin, Z. "Failure Criteria for Unidirectional Fiber Composites." *Journal of Applied Mechanics*, vol. 47, pp. 329-334, 1980.

- Hercules Bacchus Works, Aerospace Products Group. "Magnamite 8551-7 Tough Resin, Graphite Prepreg Tape and Fabric Summary." Magna, UT, November (1985) and Product Data Sheet.
- Jiang, J. and R. C. Tennyson. "Closure of the Cubic Tensor Polynomial Failure Surface." *Journal of Composite Materials*, vol. 23, pp.208-231, 1989.
- Nahas, M. N. "Survey of Failure and Post-Failure Theories of Laminated Fiber-Reinforced Composites." *Journal of Composites Technology and Research*, vol. 8, pp. 138-153, 1986.
- Tsai, S. W., and E. M. Wu. "A General Theory of Strength for Anisotropic Materials." *Journal of Composite Materials*, vol. 5, pp. 58-80, 1971.
- Tsai, S. W. *Composites Design, Fourth Edition*. Think Composites, Dayton, OH, 1987.
- Welsh, J.S. and D.F. Adams, "Unidirectional Composite Compression Strengths Obtained by Testing Cross-Ply Laminates." *Journal of Composites Technology & Research*. vol. 18, no. 4, pp. 241-248, 1996.
- Welsh, J. S. and D. F. Adams, "Testing of Angle-Ply Laminates to Obtain Unidirectional Composite Compression Strengths." *Composites Part A*. vol. 28A, pp. 387-396, 1997.
- Wilson, D. W., V. Altstadt, M. Maier, J. Prandy, K. Thoma, and D. Vinckier. "An Analytical and Experimental Evaluation of 0/90 Laminate Tests for Compression Characterization." *Journal of Composites Technology and Research*, vol. 16, no. 2, pp. 146-153, 1994.

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	DEFENSE TECHNICAL INFORMATION CENTER DTIC DDA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	HQDA DAMO FDQ D SCHMIDT 400 ARMY PENTAGON WASHINGTON DC 20310-0460
1	OSD OUSD(A&T)/ODDDR&E(R) R J TREW THE PENTAGON WASHINGTON DC 20301-7100
1	DPTY CG FOR RDE HQ US ARMY MATERIEL CMD AMCRD MG CALDWELL 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	INST FOR ADVNCD TCHNLGY THE UNIV OF TEXAS AT AUSTIN PO BOX 202797 AUSTIN TX 78720-2797
1	DARPA B KASPAR 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
1	NAVAL SURFACE WARFARE CTR CODE B07 J PENNELLA 17320 DAHLGREN RD BLDG 1470 RM 1101 DAHLGREN VA 22448-5100
1	US MILITARY ACADEMY MATH SCI CTR OF EXCELLENCE DEPT OF MATHEMATICAL SCI MAJ M D PHILLIPS THAYER HALL WEST POINT NY 10996-1786

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	DIRECTOR US ARMY RESEARCH LAB AMSRL DD J J ROCCHIO 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CS AS (RECORDS MGMT) 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI LL 2800 POWDER MILL RD ADELPHI MD 20783-1145
	<u>ABERDEEN PROVING GROUND</u>
4	DIR USARL AMSRL CI LP (305)

<u>NO. OF</u> <u>COPIES</u>	<u>ORGANIZATION</u>
1	DIRECTOR USARL AMSRL CP CA D SNIDER 2800 POWDER MILL RD ADELPHI MD 20783
1	COMMANDER US ARMY ARDEC AMSTA AR FSE T GORA PICATINNY ARSENAL NJ 07806-5000
3	COMMANDER US ARMY ARDEC AMSTA AR TD PICATINNY ARSENAL NJ 07806-5000
5	US ARMY TACOM AMSTA JSK S GOODMAN J FLORENCE AMSTA TR D B RAJU L HINOJOSA D OSTBERG WARREN MI 48397-5000
5	PM SADARM SFAE GCSS SD COL B ELLIS M DEVINE W DEMASSI J PRITCHARD S HROWNAK PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC F MCLAUGHLIN PICATINNY ARSENAL NJ 07806

<u>NO. OF</u> <u>COPIES</u>	<u>ORGANIZATION</u>
4	COMMANDER US ARMY ARDEC AMSTA AR CCH S MUSALLI R CARR M LUCIANO T LOUCEIRO PICATINNY ARSENAL NJ 07806-5000
2	COMMANDER US ARMY ARDEC AMSTA AR E FENNELL PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR CCH PICATINNY ARSENAL NJ 07806-5000
2	COMMANDER US ARMY ARDEC AMSTA AR PICATINNY ARSENAL NJ 07806-5000
3	COMMANDER US ARMY ARDEC AMSTA AR CCH P J LUTZ AMSTA AR FSF T C LIVECCHIA AMSTA AR QAC T/C C PATEL PICATINNY ARSENAL NJ 07806-5000
2	COMMANDER US ARMY ARDEC AMSTA AR M D DEMELLA F DIORIO PICATINNY ARSENAL NJ 07806-5000

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
3	COMMANDER US ARMY ARDEC AMSTA AR FSA A WARNASH B MACHAK M CHIEFA PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER WATERVLIET ARSENAL SMCWV QAE Q B VANINA BLDG 44 WATERVLIET NY 12189-4050
1	COMMANDER WATERVLIET ARSENAL SMCWV SPM T MCCLOSKEY BLDG 253 WATERVLIET NY 12189-4050
8	DIRECTOR BENET LABORATORIES AMSTA AR CCB J KEANE J BATTAGLIA J VASILAKIS G FFIAR V MONTVORI G DANDREA R HASENBEIN SMCAR CCB R S SOPOK WATERVLIET NY 12189
1	COMMANDER WATERVLIET ARSENAL SMCWV QA QS K INSCO WATERVLIET NY 12189-4050
1	COMMANDER US ARMY ARDEC PRDCTN BASE MODERN ACTY AMSMC PBM K PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY BELVOIR RD&E CTR STRBE JBC FT BELVOIR VA 22060-5606

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	COMMANDER US ARMY ARDEC AMSTA AR FSP G M SCHIKSNIS D CARLUCCI PICATINNY ARSENAL NJ 07806-5000
1	US ARMY COLD REGIONS RESEARCH & ENGINEERING LABORATORY P DUTTA 72 LYME RD HANOVER NH 03755
1	DIRECTOR USARL AMSRL WT L D WOODBURY 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	COMMANDER US ARMY AMCOM AMSMI RD W MCCORKLE AMSMI RD ST P DOYLE AMSMI RD ST CN T VANDIVER REDSTONE ARSENAL AL 35898-5247
2	US ARMY RESEARCH OFFICE A CROWSON J CHANDRA PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709-2211
3	US ARMY RESEARCH OFFICE ENGINEERING SCIENCES DIV R SINGLETON G ANDERSON K IYER PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709-2211

<u>NO. OF</u> <u>COPIES</u>	<u>ORGANIZATION</u>
5	PROJECT MANAGER TANK MAIN ARMAMENT SYSTEMS SFAE GSSC TMA COL PAWLICKI K KIMKER E KOPACZ R ROESER B DORCY PICATINNY ARSENAL NJ 07806-5000
1	PROJECT MANAGER TANK MAIN ARMAMENT SYS SFAE GSSC TMA SMD R KOWALSKI PICATINNY ARSENAL NJ 07806-5000
2	PEO FIELD ARTILLERY SYSTEMS SFAE FAS PM H GOLDMAN T MCWILLIAMS PICATINNY ARSENAL NJ 07806-5000
2	PROJECT MANAGER CRUSADER G DELCOCO J SHIELDS PICATINNY ARSENAL NJ 07806-5000
2	NASA LANGLEY RESEARCH CTR AMSRL VS MS 266 W ELBER F BARTLETT JR HAMPTON VA 23681-0001
2	COMMANDER DARPA J KELLY B WILCOX 3701 N FAIRFAX DR ARLINGTON VA 22203-1714

<u>NO. OF</u> <u>COPIES</u>	<u>ORGANIZATION</u>
6	COMMANDER WRIGHT PATTERSON AFB WL FIV A MAYER WL MLBM S DONALDSON T BENSON-TOLLE C BROWNING J MCCOY F ABRAHAMS 2941 P STREET STE 1 DAYTON OH 45433
1	NAVAL SURFACE WARFARE CTR DAHLGREN DIV CODE G06 DAHLGREN VA 22448
1	NAVAL RESEARCH LABORATORY I WOLOCK CODE 6383 WASHINGTON DC 20375-5000
1	OFFICE OF NAVAL RESEARCH MECH DIV CODE 1132SM Y RAJAPAKSE ARLINGTON VA 22217
1	NAVAL SURFACE WARFARE CTR CRANE DIVISION M JOHNSON CODE 20H4 LOUISVILLE KY 40214-5245
1	DAVID TAYLOR RESEARCH CTR SHIP STRUCTURES & PROTECTION DEPARTMENT J CORRADO CODE 1702 BETHESDA MD 20084
2	DAVID TAYLOR RESEARCH CTR R ROCKWELL W PHYLLAIER BETHESDA MD 20054-5000
1	DEFENSE NUCLEAR AGENCY INNOVATIVE CONCEPTS DIV R ROHR 6801 TELEGRAPH RD ALEXANDRIA VA 22310-3398

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	EXPEDITIONARY WARFARE DIV F SHOUP N85 2000 NAVY PENTAGON WASHINGTON DC 20350-2000
1	OFFICE OF NAVAL RESEARCH D SIEGEL 351 800 N QUINCY ST ARLINGTON VA 22217-5660
1	NAVAL SURFACE WARFARE CTR J H FRANCIS CODE G30 DAHLGREN VA 22448
2	NAVAL SURFACE WARFARE CTR D WILSON CODE G32 R D COOPER CODE G32 DAHLGREN VA 22448
4	NAVAL SURFACE WARFARE CTR J FRAYSSE CODE G33 E ROWE CODE G33 T DURAN CODE G33 L DE SIMONE CODE G33 DAHLGREN VA 22448
1	COMMANDER NAVAL SEA SYSTEMS CMD D LIESE 2531 JEFFERSON DAVIS HIGHWAY ARLINGTON VA 22242-5160
1	NAVAL SURFACE WARFARE CTR M E LACY CODE B02 17320 DAHLGREN RD DAHLGREN VA 22448
1	NAVAL SURFACE WARFARE CTR TECH LIBRARY CODE 323 17320 DAHLGREN RD DAHLGREN VA 22448
4	DIRECTOR LLNL R CHRISTENSEN S DETERESA F MAGNESS M FINGER PO BOX 808 LIVERMORE CA 94550

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	LOS ALAMOS NATL LAB F ADDESSIO MS B216 PO BOX 1633 LOS ALAMOS NM 87545
1	LOS ALAMOS NATL LAB J REPPA MS F668 PO BOX 1663 LOS ALAMOS NM 87545
1	OAK RIDGE NATIONAL LABORATORY R M DAVIS PO BOX 2008 OAK RIDGE TN 37831-6195
1	PENNSYLVANIA STATE UNIVERSITY C BAKIS 227 N HAMMOND UNIVERSITY PARK PA 16802
3	UNITED DEFENSE LP 4800 EAST RIVER RD P JANKE MS170 T GIOVANETTI MS236 B VAN WYK MS389 MINNEAPOLIS MN 55421-1498
4	DIRECTOR SANDIA NATL LABORATORIES APPLIED MECHANICS DEPT DIVISION 8241 W KAWAHARA K PERANO D DAWSON P NIELAN PO BOX 969 LIVERMORE CA 94550-0096
1	DREXEL UNIVERSITY A S D WANG 32ND AND CHESTNUT ST PHILADELPHIA PA 19104
1	BATTELLE C R HARGREAVES 505 KING AVE COLUMBUS OH 43201-2681

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	PACIFIC NORTHWEST LABORATORY M SMITH PO BOX 999 RICHLAND WA 99352
1	LLNL M MURPHY PO BOX 808 L 282 LIVERMORE CA 94550
1	NORTH CAROLINA STATE UNIVERSITY CIVIL ENGINEERING DEPT W RASDORF PO BOX 7908 RALEIGH NC 27696-7908
1	PENNSYLVANIA STATE UNIVERSITY R MCNITT 227 HAMMOND BLDG UNIVERSITY PARK PA 16802
1	PENNSYLVANIA STATE UNIVERSITY R S ENGEL 245 HAMMOND BLDG UNIVERSITY PARK PA 16801
1	PURDUE UNIVERSITY SCHOOL OF AERO & ASTRO C T SUN W LAFAYETTE IN 47907-1282
1	STANFORD UNIVERSITY DEPT OF AERONAUTICS AND AEROBALLISTICS DURANT BUILDING S TSAI STANFORD CA 94305
1	UCLA MANE DEPT ENGR IV H THOMAS HAHN LOS ANGELES CA 90024-1597

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	U OF DAYTON RSCH INSTITUTE R Y KIM A K ROY 300 COLLEGE PARK AVE DAYTON OH 45469-0168
1	UNIVERSITY OF DAYTON J M WHITNEY COLLEGE PARK AVE DAYTON OH 45469-0240
2	UNIVERSITY OF DELAWARE CTR FOR COMPOSITE MATERIALS J GILLESPIE M SANTARE 201 SPENCER LABORATORY NEWARK DE 19716
1	UNIV OF ILLINOIS AT URBANA CHAMPAIGN NATL CTR FOR COMPOSITE MATERIALS RESEARCH 216 TALBOT LABORATORY J ECONOMY 104 S WRIGHT STREET URBANA IL 61801
1	UNIVERSITY OF KENTUCKY L PENN 763 ANDERSON HALL LEXINGTON KY 40506-0046
1	UNIVERSITY OF UTAH DEPT OF MECH & INDUSTRIAL ENGR S SWANSON SALT LAKE CITY UT 84112
2	UNIV OF TEXAS AT AUSTIN CTR FOR ELECTROMECHANICS A WALLS J KITZMILLER 10100 BURNET RD AUSTIN TX 78758-4497

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
3	VA POLYTECHNICAL INSTITUTE & STATE UNIVERSITY DEPT OF ESM M W HYER K REIFSNIDER R JONES BLACKSBURG VA 24061-0219
1	UNIVERSITY OF MARYLAND DEPT OF AEROSPACE ENGR A J VIZZINI COLLEGE PARK MD 20742
1	AAI CORPORATION T G STASTNY PO BOX 126 HUNT VALLEY MD 21030-0126
1	JOHN HEBERT G CHRYSSOMALLIS PO BOX 1072 HUNT VALLEY MD 21030-0126
1	ARMTEC DEFENSE PRODUCTS S DYER 85 901 AVE 53 PO BOX 848 COACHELLA CA 92236
2	ADVANCED COMPOSITE MATERIALS CORPORATION P HOOD J RHODES 1525 S BUNCOMBE RD GREER SC 29651-9208
1	SAIC D DAKIN 2200 POWELL ST STE 1090 EMERYVILLE CA 94608
1	SAIC M PALMER 2109 AIR PARK RD S E ALBUQUERQUE NM 87106
1	SAIC R ACEBAL 1225 JOHNSON FERRY RD STE 100 MARIETTA GA 30068

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	SAIC G CHRYSSOMALLIS 3800 W 80TH STREET STE 1090 BLOOMINGTON MN 55431
6	ALLIANT TECH SYSTEMS INC C CANDLAND R BECKER L LEE C AACHUS D KAMDAR D FISHER 600 2ND ST NE HOPKINS MN 55343-8367
1	AMOCO PERFORMANCE PRODUCTS INC M MICHNO JR 4500 MCGINNIS FERRY RD ALPHARETTA GA 30202-3944
1	APPLIED COMPOSITES W GRISCH 333 NORTH SIXTH ST ST CHARLES IL 60174
1	BRUNSWICK DEFENSE T HARRIS STE 410 1745 JEFFERSON DAVIS HWY ARLINGTON VA 22202
1	PROJECTILE TECHNOLOGY INC 515 GILES ST HAVRE DE GRACE MD 21078
1	CUSTOM ANALYTICAL ENGR SYS INC A ALEXANDER 13000 TENSOR LANE NE FLINTSTONE MD 21530
1	NOESIS INC A BOUTZ 1110 N GLEBE RD STE 250 ARLINGTON VA 22201-4795

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	ARROW TECH ASSO 1233 SHELBURNE RD STE D 8 SOUTH BURLINGTON VT 05403-7700
1	NAVAL SURFACE WARFARE CTR R HUBBARD G33-C DAHLGREN DIVISION DAHLGREN VA 2248-5000
5	GEN CORP AEROJET D PILLASCH T COULTER C FLYNN D RUBAREZUL M GREINER 1100 WEST HOLLYVALE ST AZUSA CA 91702-0296
7	CIVIL ENGR RSCH FOUNDATION H BERNSTEIN PRESIDENT C MAGNELL K ALMOND R BELLE M WILLETT E DELO B MATTES 1015 15TH ST NW STE 600 WASHINGTON DC 20005
1	NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY STRUCTURE & MECHANICS GP POLYMER DIV POLYMERS G MCKENNA RM A209 GAITHERSBURG MD 20899
1	DUPONT COMPANY COMPOSITES ARAMID FIBERS S BORLESKE DEVELOPMENT MGR CHESNUT RUN PLAZA PO BOX 80702 WILMINGTON DE 19880-0702
1	GENERAL DYNAMICS LAND SYSTEMS DIVISION D BARTLE PO BOX 1901 WARREN MI 48090

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
3	HERCULES INC R BOE F POLICELLI J POESCH PO BOX 98 MAGNA UT 84044
3	HERCULES INC G KUEBELER J VERMEYCHUK B MANDERVILLE JR HERCULES PLZ WILMINGTON DE 19894
1	HEXCEL M SHELENDICH 11555 DUBLIN BLVD PO BOX 2312 DUBLIN CA 94568-0705
4	INSTITUTE FOR ADVANCED TECH H FAIR P SULLIVAN W REINECKE I MCNAB 4030 2 W BRAKER LN AUSTIN TX 78759
1	INTEGRATED COMPOSITE TECH H PERKINSON JR PO BOX 397 YORK NEW SALEM PA 17371-0397
1	INTERFEROMETRICS INC R LARRIVA VICE PRESIDENT 8150 LEESBURG PIKE VIENNA VA 22100
1	AEROSPACE RES & DEV (ASRDD) CORP D ELDER PO BOX 49472 COLORADO SPRINGS CO 80949-9472
1	PM ADVANCED CONCEPTS LORAL VOUGHT SYSTEMS J TAYLOR MS WT 21 PO BOX 650003 DALLAS TX 76265-0003

NO. OF
COPIES ORGANIZATION

2 LORAL VOUGHT SYSTEMS
G JACKSON
K COOK
1701 W MARSHALL DR
GRAND PRAIRIE TX 75051

1 BRIGS CO
J BACKOFEN
2668 PETERBOROUGH ST
HERDON VA 22071-2443

1 SOUTHWEST RSCH INSTITUTE
J RIEGEL
ENGR & MATL SCIENCES DIV
6220 CULEBRA RD
PO DRAWER 28510
SAN ANTONIO TX 78228-0510

1 ZERNOW TECHNICAL SERVICES
L ZERNOW
425 W BONITA AVE SUITE 208
SAN DIMAS CA 91773

1 R EICHELBERGER CONSULTANT
409 W CATHERINE ST
BEL AIR MD 21014-3613

1 DYNA EAST CORPORATION
P CHI CHOU
3201 ARCH ST
PHILADELPHIA PA 19104-2711

2 MARTIN MARIETTA CORP
P DEWAR
L SPONAR
230 EAST GODDARD BLVD
KING OF PRUSSIA PA 19406

2 OLIN CORPORATION
FLINCHBAUGH DIV
E STEINER
B STEWART
PO BOX 127
RED LION PA 17356

1 OLIN CORPORATION
L WHITMORE
10101 9TH ST NORTH
ST PETERSBURG FL 33702

NO. OF
COPIES ORGANIZATION

1 RENNSAELER POLYTECHNIC
INSTITUTE
R B PIPES
PRESIDENT OFC PITTSBURGH BLDG
TROY NY 12180-3590

1 SPARTA INC
J GLATZ
9455 TOWNE CTR DRIVE
SAN DIEGO CA 92121-1964

2 UNITED DEFENSE LP
P PARA
G THOMAS
1107 COLEMAN AVE BOX 367
SAN JOSE CA 95103

1 MARINE CORPS SYSTEMS COMMAND
PM GROUND WPNS
COL R OWEN
2083 BARNETT AVE SUITE 315
QUANTICO VA 22134-5000

1 OFFICE OF NAVAL RES
J KELLY
800 NORTH QUINCEY ST
ARLINGTON VA 22217-5000

2 NAVAL SURFACE WARFARE CTR
CARDEROCK DIVISION
R CRANE CODE 2802
C WILLIAMS CODE 6553
3A LEGGETT CIR
ANNAPOLIS MD 21402

5 SIKORSKY
H BUTTS
T CARSTENSAN
B KAY
S GARBO
J ADELMANN
6900 MAIN ST
PO BOX 9729
STRATFORD CT 06601-1381

1 U WYOMING
D ADAMS
PO BOX 3295
LARAMIE WY 82071

<u>NO. OF</u> <u>COPIES</u>	<u>ORGANIZATION</u>
1	MICHIGAN ST UNIVERSITY R AVERILL 3515 EB MSM DEPT EAST LANSING MI 48824-1226
1	AMOCO POLYMERS J BANISAUKAS 4500 MCGINNIS FERRY RD ALPHARETTA GA 30005
1	HEXCEL T BITZER 11711 DUBLIN BLVD DUBLIN CA 94568
1	BOEING R BOHLMANN PO BOX 516 MC 5021322 ST LOUIS MO 63166-0516
1	NAVSEA OJRI G CAMPONESCHI 2351 JEFFERSON DAVIS HWY ARLINGTON VA 22242-5160
1	LOCKHEED MARTIN R FIELDS 1195 IRWIN CT WINTER SPRINGS FL 32708
1	USAF WL MLS OL A HAKIM 5225 BAILEY LOOP 243E MCCLELLAN AFB CA 55552
1	PRATT & WHITNEY D HAMBRICK 400 MAIN ST MS 114-37 EAST HARTFORD CT 06108
1	BOEING DOUGLAS PRODUCTS DIV L J HART-SMITH 3855 LAKEWOOD BLVD D800-0019 LONG BEACH CA 90846-0001

<u>NO. OF</u> <u>COPIES</u>	<u>ORGANIZATION</u>
1	MIT P LAGACE 77 MASS AVE CAMBRIDGE MA 01887
1	NASA-LANGLEY J MASTERS MS 389 HAMPTON VA 23662-5225
1	CYTEC M LIN 1440 N KRAEMER BLVD ANAHEIM CA 92806
2	BOEING ROTORCRAFT P MINGURT P HANDEL 800 B PUTNAM BLVD WALLINGFORD PA 19086
2	FAA TECH CENTER D OPLINGER AAR-431 P SHYPRYKEVICH AAR-431 ATLANTIC CITY NJ 08405
1	NASA-LANGLEY RC C C POE MS 188E NEWPORT NEWS VA 23608
1	LOCKHEED MARTIN S REEVE 8650 COBB DR D 73 62 MZ 0648 MARIETTA GA 30063-0648
1	WL MLBC E SHINN 2941 PST STE 1 WRIGHT PAT AFB OH 45433-7750
2	IIT RESEARCH CENTER D ROSE 201 MILL ST ROME NY 13440-6916
1	MATERIALS SCIENCES CORP B W ROSEN 500 OFFICE CENTER DR STE 250 FORT WASHINGTON PA 19034

<u>NO. OF</u> <u>COPIES</u>	<u>ORGANIZATION</u>
1	DOW UT S TIDRICK 15 STERLING DR WALLINGFORD CT 06492
3	TUSKEGEE UNIVERISTY MATERIALS RESEARCH LAB SCHOOL OF ENGR & ARCH S JEELANI H MAHFUZ U VAIDYA TUSKEGEE AL 36088
4	NIST POLYMERS DIVISION R PARNAS J DUNKERS M VANLANDINGHAM D HUNSTON GAITHERSBURG MD 20899
2	NORTHROP GRUMMAN ENVIRONMENTAL PROGRAMS R OSTERMAN 8900 E WASHINGTON BLVD PICO RIVERA CA 90660
1	OAK RIDGE NATL LAB A WERESZCZAK BLDG 4515 MS 6069 PO BOX 2008 OAKRIDGE TN 37831-6064
1	COMMANDER USARDEC INDUSTRIAL ECOLOGY CTR T SACHAR BLDG 172 PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER USA AMCOM AVIATION APPLIED TECH DIR J SCHUCK FT EUSTIS VA

<u>NO. OF</u> <u>COPIES</u>	<u>ORGANIZATION</u>
1	COMMANDER US ARMY ARDEC AMSTA AR SRE D YEE PICATINNY ARSENAL NJ 07806-5000
7	COMMANDER US ARMY ARDEC AMSTA AR CCH B B KONRAD E RIVERA G EUSTICE S PATEL G WAGNECZ R SAYER F CHANG BLDG 65 PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR QAC T D RIGOGLIOSO BLDG 354 M829E3 IPT PICATINNY ARSENAL NJ 07806-5000
	<u>ABERDEEN PROVING GROUND</u>
72	DIR USARL AMSRL CI AMSRL CI HA W STUREK A MARK AMSRL IS CD R KASTE AMSRL SL B AMSRL SL BA AMSRL SL BE D BELY AMSRL SL I AMSRL WM B A HORST E SCHMIDT AMSRL WM BE G WREN C LEVERITT D KOOKER

NO. OF
COPIES ORGANIZATION

AMSRL WM BC
P PLOSTINS
D LYON
J NEWILL
S WILKERSON
AMSRL WM BD
R FIFER
B FORCH
R PESCE RODRIGUEZ
B RICE
AMSRL WM M
D VIECHNICKI
G HAGNAUER
J MCCAULEY
AMSRL WM MA
R SHUFORD
S MCKNIGHT
AMSRL WM MB
B BURNS
W DRYSDALE
J BENDER
T BLANAS
T BOGETTI
R BOSSOLI
L BURTON
S CORNELISON
P DEHMER
R DOOLEY
B FINK
G GAZONAS
S GHIORSE
D GRANVILLE
D HOPKINS
C HOPPEL
D HENRY
R KASTE
M LEADORE
R LIEB
E RIGAS
D SPAGNUOLO
W SPURGEON
E SZYMANSKI
J TZENG
A ABRAHAMIAN
M BERMAN
A FRYDMAN
T LI
W MCINTOSH
AMSRL WM MC
J BEATTY

NO. OF
COPIES ORGANIZATION

AMSRL WM MD
W ROY
AMSRL WM TA
W GILLICH
E RAPACKI
T HAVEL
AMSRL WM TC
R COATES
W DE ROSSET
AMSRL WM TD
D DIETRICH
W BRUCHEY
A DAS GUPTA
AMSRL WM BB
H ROGERS
AMSRL WM BA
F BRANDON
W D AMICO
AMSRL WM BR
J BORNSTEIN
AMSRL WM TE
A NIILER
AMSRL WM BF
J LACETERA

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project(0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE June 1999	3. REPORT TYPE AND DATES COVERED Final, October 1997 - April 1999	
4. TITLE AND SUBTITLE Effect of an Angle-Ply Orientation on Compression Strength of Composite Laminates			5. FUNDING NUMBERS 622618.AH80	
6. AUTHOR(S) Christopher P. R. Hoppel and Steven J. De Teresa*				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: AMSRL-WM-MB Aberdeen Proving Ground, MD 21005-5069			8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-2003	
9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES *Lawrence Livermore National Laboratory Livermore, CA 94550				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) An experimental program was initiated to investigate the effect of angle-ply orientations on the compressive strength (X1C) of 0° plies in fiber-reinforced composite laminates. Graphite fiber-reinforced epoxy test coupons with the generic architecture [0 _z /±θ] (where θ varied between 0° and 90°) and for the quasi-isotropic architecture were evaluated. The effective compressive strength of the 0° plies varied considerably. The results were related to the Poisson's ratios of the laminates, with high Poisson's ratios leading to high transverse tensile strains in the test coupons and lower-than-expected strengths. Specimens with the [0 _z /±30] architecture had both the highest Poisson's ratio and the lowest calculated ply-level compression strength for the 0° plies. This work has implications in the selection of composite failure criteria for compression performance, design of test coupons for acceptance testing and the selection of laminate architectures for optimum combinations of compressive and shear behavior. Two commonly used composite failure criteria, the maximum stress and the Tsai-Wu, predict significantly different laminate strengths depending on the Poisson's ratio of the laminate. This implies that the biaxial stress state in the laminate needs to be carefully considered before backing out unidirectional properties.				
14. SUBJECT TERMS composites, compression, failure criteria			15. NUMBER OF PAGES 34	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-2003 (Hoppel) Date of Report June 1999

2. Date Report Received _____

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) _____

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) _____

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. _____

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) _____

CURRENT
ADDRESS

Organization

Name

E-mail Name

Street or P.O. Box No.

City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD
ADDRESS

Organization

Name

Street or P.O. Box No.

City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)
(DO NOT STAPLE)

DEPARTMENT OF THE ARMY

OFFICIAL BUSINESS



**NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES**

BUSINESS REPLY MAIL
FIRST CLASS PERMIT NO 0001,APG,MD

POSTAGE WILL BE PAID BY ADDRESSEE

**DIRECTOR
US ARMY RESEARCH LABORATORY
ATTN AMSRL WM MB
ABERDEEN PROVING GROUND MD 21005-5069**

