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Static Strength Prediction of Bolted Joint in Composite Material

B. L. Agarwal*
Northrop Corporation, Hawthorne, Calif.

A new method of predicting the strength of double-shear single-fastener composite joints is presented. The analysis method consists of calculating the stress distribution around a fastener hole using a finite-element analysis and predicting the various modes of laminate failure through the use of the average stress criterion as originally suggested and through some modifications to the criterion. Several joint configurations of a composite bolt bearing specimen have been analyzed using the method. The net tension and bearing and shearout modes of failures have been predicted analytically. The analytical predictions have been compared with available experimental data and good correlation has been obtained.

Introduction

As composites now appear to be ready for production commitments in heavily loaded components and in major structural areas of wings, fuselages, empennage structures, etc., it is vital that technically lagging areas be brought up to the point where confidence in these areas is at acceptable levels. One of the prime areas lagging is the strength prediction of composite bolted joints. The main objective of this paper is to present a method for the accurate prediction of the static strength of a single-fastener composite joint, considering all of the various possible failure modes in the composite material.

There have been very few investigations into the analysis and strength prediction of composite bolted joints. In Ref. 1, the finite-element approach was used to predict the failure mode and the strength of an anisotropic bolt bearing specimen. The problem was modeled by using membrane elements and assuming a cosine normal load distribution to be acting along half of the bolt surface. The stress distribution obtained in this manner was fairly accurate. In order to predict the failure mode and failure load, the distortional energy failure criterion was used on each individual lamina. It was generally possible to predict the failure mode, but the failure loads were conservative by as much as 50%. Oplinger and Gandhi[2] considered the plate/fastener system as a rectangular orthotropic plate containing rigid circular inclusions which exert load by responding to an assumed displacement in a given direction. The contact was initially assumed to be frictionless, but later the work was extended to account for the effects of pin friction. The analytical results were obtained by the least-squares collocation in conjunction with a complex variable formulation for the two-dimensional theory of orthotropic elastic plates. This approach gave a slightly more accurate stress analysis than that used in Ref. 1. The failure criterion used was Hoffman's modified distortional energy criterion. The main advantage of this criterion is that the differences between tensile and compressive strengths, which are characteristic of many composite materials, can be taken into consideration. Again, the analytical results were very conservative for most of the cases studied.

Eisenmann[3] presented a method for predicting the failure load and failure location of bolted joints in composite materials. The method is based upon assuming a stress intensity region in the vicinity of the fastener hole. The laminate fracture toughness measured by experiments is compared with the value of the mode I stress intensity derived analytically at selected points on the boundary of the fastener hole. Eight equally spaced points are chosen on the fastener boundary. The stress intensity factors are calculated for various unit load conditions, and superposition is used to determine the stress intensity at any given point. In calculating stress intensities for a unit load condition, it is assumed that a through-crack of length a^i is extending radially at location i, and the distance a^i is determined by measuring the laminate strength and fracture toughness in a direction tangent to the point on the circle. This approach was shown to yield excellent correlation with test data; however, the difficulties associated with the analysis of a radial crack emanating from a hole in a finite-width laminate when the hole is in contact with a fastener led to the use of an approximate stress analysis. Empirical corrections were added to improve the stress analysis beyond the capability of the approximate stress analysis. It is not clear whether the corrections were necessary to correct the stress analysis or the failure theory.

The approach presented herein is a simple yet accurate way of assessing joint strength, and it is capable of addressing many of the failure modes present in bolted joints. It is based

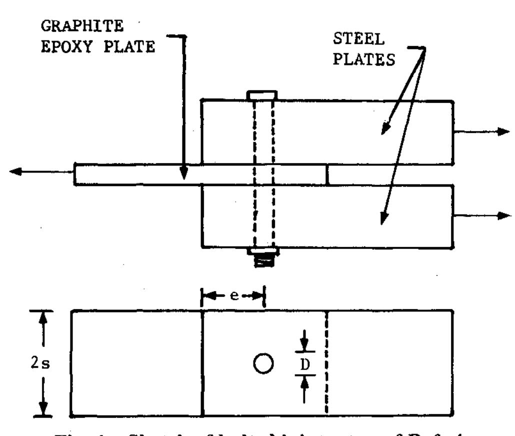

Fig. 1 Sketch of bolted joint setup of Ref. 4.

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*Senior Engineer, Structural Mechanics Research, Structural Mechanics Research Dept., Aircraft Group.

upon the use of finite elements to determine stresses and the average stress criterion to assess criticality. Although the approach presented in this paper is not directly applicable to the multifastener joints, the failure of composite laminate in the vicinity of the fastener holes can be predicted using this approach, provided that the load distribution in the joint is known.

Approach

In the present paper, an analytical method for the prediction of the static strength of single-fastener composite joints is developed. The development of the analytical model is based upon the test specimens of Ref. 4. A sketch of the joint arrangement used in Ref. 4 is shown in Fig. 1. It is noted that the graphite/epoxy laminate was placed in between two relatively thick steel plates and was attached by means of a single bolt. The analytical model developed in this paper consists of three basic steps: 1) determination of stress distribution around the fastener hole, 2) determination of the basic laminate strength, and 3) prediction of bolted joint strength and failure mode. Each of these steps is described in detail in the following subsections.

Determination of Stress Distribution around Fastener Hole

A finite-element computer code, NASTRAN, is used to determine the stress distribution around the fastener hole. The finite-element model of the double-shear bolt bearing specimen studied experimentally in Ref. 4 (Fig. 1) is presented in Figs. 2 and 3. The composite plate was divided into 284 CQDMEMI elements which are isoparametric membrane elements and do not include any bending. The plate was assumed to be symmetric about the x axis. An enlarged view of the shaded area of Fig. 2 is presented in Fig. 3. The fastener load is modeled by applying a constant displacement at one end of the plate and the load is reacted at the hole by assuming that the radial displacements of the nodes on half of the hole circumference are zero (dotted nodes in Fig. 3). This model in effect assumes a rigid frictionless bolt, and the contact surface between the bolt and the laminate is assumed to be half of the bolt circumference.

Determination of Basic Laminate Strength

The basic laminate strength (unnotched laminate strength) is determined through the use of maximum strain theory. A simplified version of this theory, which is presented in Ref. 5,

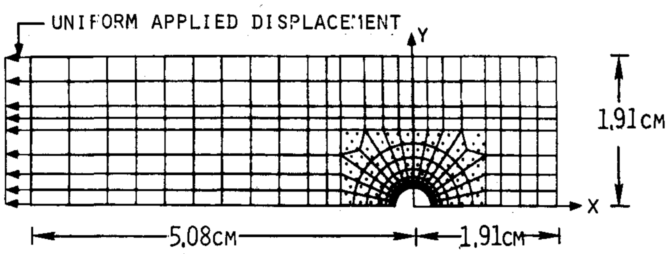


Fig. 2 NASTRAN model for bolt bearing specimen.

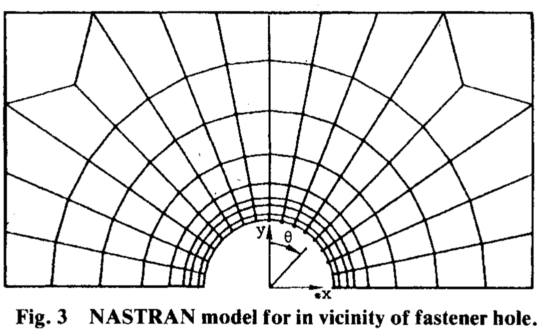


Fig. 3 NASTRAN model for in vicinity of fastener hole.

is used in the present study to predict the laminate strength and is presented here for the sake of completeness.

First, the laminate elastic properties are determined as:

$$E_x = (A_{11} - A_{12}^2/A_{22})/t, \quad E_y = (A_{22} - A_{12}^2/A_{11})/t$$

$$\nu_{xy} = A_{12}/A_{22}, \quad G_{xy} = A_{66}/t \tag{1}$$

where A_{ij} are the terms of the extensional stiffness matrix of the laminate determined from the individual ply properties as defined in Ref. 6 and t is the laminate thickness. E_x, E_y, ν_{xy}, and G_{xy} are the elastic constants of the laminate. It should be noted that the laminate is assumed to be orthotropic in the above formulation.

Knowing the elastic properties of the laminate, the strength of the laminate in tension or compression can be determined through the use of Eqs. (2). The value of applied stress σ_{1k}, σ_{2k}, and σ_{3k} (which results in the failure of the kth lamina along the fiber direction, transverse to the fiber direction, or in shear) is determined for each layer from Eq. (1) by substituting the lamina strain allowables ($\epsilon_1, \epsilon_2, \epsilon_{12}$) for a unidirectional laminate in tension or compression as the case may be. The minimum value of stress calculated in this manner gives the laminate allowable tension or compression stress. Similarly Eqs. (3) are used to determine the laminate strength in shear

$$\sigma_{1k} = \frac{\epsilon_1 E_x}{(m^2 - \nu_{xy} n^2)}, \sigma_{2k} = \frac{\epsilon_2 E_x}{(n^2 - \nu_{xy} m^2)}, \sigma_{3k} = \frac{\nu_{12} E_x}{2mn(1+\nu_{xy})} \tag{2}$$

$$\tau_{1k} = \frac{\epsilon_1 G_{xy}}{mn}, \quad \tau_{2k} = \frac{\epsilon_2 G_{xy}}{mn}, \quad \tau_{3k} = \frac{\nu_{12} G_{xy}}{(m^2 - n^2)} \tag{3}$$

where $m = \cos\theta$, $n = \sin\theta$, and θ = the angle between the laminate axial direction and the lamina fiber direction.

Prediction of Bolted Joint Strength and Failure Mode

In the present paper the average stress failure criterion[7] has been used to predict the failure load and mode of failure. The average stress failure criterion is based upon the principle that a laminate having a notch will fail when the average stress over a distance a_0 reaches the value of the unnotched laminate strength. This criterion has been used to predict the tension strength of notched laminates in Ref. 7. The average stress failure criterion as applied to bolted joints is described below.

The tension, compression (bearing), and shearout modes of failure are predicted by the scheme described in Fig. 4. For tension failure the stresses normal to the radial direction are averaged over a distance a_{0t} along several radial lines. Failure is predicted along the line where the average stress reaches the laminate tensile strength in the direction tangent to the point on the circumference under consideration (lines AB). The distance a_{0t} in the present approach is assumed to be 0.229

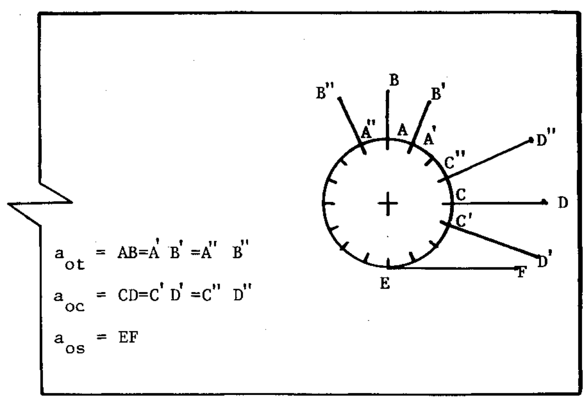


Fig. 4 Direction of integration for average stress failure criterion.

cm, which was found to result in excellent correlation of experimental and analytical data in Ref. 8 for the AS/3501-5 graphite/epoxy system. Although the material used in the test coupons of Ref. 4 is T300/SP286, it is believed that the change in the values of a_{0t} for similar graphite/epoxy material systems is relatively small.

The bearing strength of the joint is predicted by averaging the radial stresses over a distance a_{0c} along several radial lines (CD) as shown in Fig. 4. A bearing failure is assumed to occur when the average radial compressive stress over a distance a_{0c} reaches the laminate compressive strength along the same line. The direction of failure is the one with the minimum strength. The distance a_{0c} in the present approach is assumed to be 0.622 cm as suggested in Ref. 8 in order to determine the compressive strength of a notched laminate.

The shearout mode of failure is predicted by calculating the average shear stress along line EF as shown in Fig. 4 over a distance a_{0s}. Since, to the author's knowledge, the distance a_{0s} is not known for any material system, the distance a_{0s} will be calculated based upon the experimental data and kept constant throughout the analytical investigation.

The analysis method presented above is equally applicable to the joints having biaxial or even more complex states of stress around the fastener hole. The stresses to be averaged are tension, compression, and shear along their respective directions for the failure modes discussed above. Only one stress needs to be considered for each failure mode. For example, in the case of the net tension failure mode, only the tensile stresses along the radial lines are needed irrespective of the state of stress.

Results and Discussion

The experimental data used in this paper for the purpose of comparison are taken from Ref. 4 and the basic characteristics of the joints analyzed are presented in Table 1. The lamina properties used in this paper are presented in Table 2. The laminate strength values for these joints were determined through the use of the criteria described earlier and are presented in Table 3. However, some modifications to the laminate failure criterion were made. In calculating the shear strength of the laminate it was necessary to modify the shear strain to be used with the maximum strain theory. Since the shear stress-strain relationship is nonlinear for a 0° lamina loaded in shear, the ultimate strain was assumed to be equal to the shear strength divided by the elastic shear modulus. However, the strain used for calculating the tensile strength of the laminate was the maximum allowable shear strain of the lamina. In calculating the ultimate tensile strength of a laminate containing 90° piles, transverse tension failure of the 90° plies was permitted to occur as it does not result in complete laminate rupture.

NASTRAN Results

The NASTRAN model used in the analysis of the bolted joints has been described. Although no attempt has been made in the present paper to compare analytical results for stress distributions with other techniques (e.g., collocation), the finite-element grid used in the analysis is considered to be fine enough to yield sufficiently accurate results. In order to determine the accuracy of the finite-element model the total number of elements in the vicinity of the fastener hole was increased by 50%. The results obtained from this new model were in very close agreement with the old model (a difference of only 2%).

A typical radial load distribution from NASTRAN has been plotted in Fig. 5. It is seen that the cosine load distribution which is often assumed for bolted joint analysis is similar to the distribution obtained using the present NASTRAN model. However, the zero radial displacement boundary conditions imposed in the present approach are more representative of a stiff bolt in thin laminates. In Ref. 2 it was shown that the cosine radial load distribution is adequate for joints when $e/D=2$ and s/D is not too large, and also the stress distribution is relatively invariant with small modifications of assumed radial load distribution. In order to estimate the effect of assumed radial load distribution on the joint strength, two very crude variations of radial load distribution are assumed as shown in the upper part of Fig. 6

Table 1 Summary of selected test data from Ref. 4

Case no.	Edge distance e, cm	Side distance a, cm	Type of laminate	Laminate thickness, mm
1	1.42	1.27	$(0/\pm45/90)_s$	1.067
2	1.91	1.91	–	1.067
3	1.42	1.91	–	1.067
4	0.97	1.91	–	1.067
5	0.97	1.27	$(0/\pm45/90)_{2s}$	2.235
6	1.42	1.27	$(0/\pm45/90/\pm45)_s$	1.676
7	1.42	1.27	$(0_2/\pm45/90)_s$	1.397
8	1.42	1.27	$(\pm45)_{2s}$	1.118
9	1.42	1.27	$(0/90)_{2s}$	1.118
10	1.42	1.27	$(0_2/\pm45)_s$	1.067

Note: All tests are room temperature static tensile tests to failure, bolt diameter = 0.476 cm.

Table 2 Material properties for T300/SP286 graphite/epoxy

	Ultimate strains, cm/cm
Longitudinal modulus E_L = 131 GPa	Longitudinal tension ϵ_L^{tu} = 9400
Transverse modulus E_T = 8.274 GPa	Transverse tension ϵ_T^{tu} = 6060
Inplane shear modulus G_{LT} = 5.033 GPa	Longitudinal compression ϵ_L^{cu} = 8270
Poisson's ratio ν_{LT} = 0.30	Transverse compression ϵ_T^{cu} = 23,400
Ultimate inplane shear strength = 50 MPa	Inplane shear γ_{LT}^{su} = 17,860

Table 3 Laminate strengths based on maximum strain theory

Laminate configuration	Tensile strength, MPa	Compressive strength, MPa	Shear strength, MPa
$(0/\pm45/90)_s$	475	418	191
$(0/\pm45/90/\pm45)_s$	392	345	238
$(0_2/\pm45/90)_S$	626	552	163
$(\pm45)_{2s}$	180	180	409
$(0/90)_{2s}$	657	578	50
$(0_2/\pm45)_s$	716	552	191

along with the distribution obtained from the NASTRAN analyses for the case 1 joint of Table 1. The effect of these variations on joint strength is shown in the lower part of Fig. 6. The tension and shearout modes of failure seem to be much less sensitive than the bearing mode of failure. The predicted bearing failure load for distribution 2 results in a significantly lower value than other distributions. However, the radial load distribution similar to distribution 2 is unlikely to occur in a bolted joint. Hence, the assumed NASTRAN model in this paper should be a good representation of the actual joint behavior.

Joint Strength and Failure Modes

The results for the 10 cases studied are presented in Table 4. The experimental results from Ref. 4 have been presented for the purpose of comparison. The analytical strengths of the bolted joints were predicted by the method discussed earlier. Since the applied load in the present case was axial tension it was found that the net tension, bearing, and shearout modes of failure were in the locations shown in Fig. 7. The failure loads for all three failure modes obtained through the use of the average stress failure criterion are presented in Table. 4. It was explained earlier that the distance a_{0s} is not known at present for any material. In order to predict the shearout failure load for a joint, a_{0s} was assumed to be 1.143 cm for those cases in which the edge distances were greater than 1.143 cm. If the edge distance was smaller than 1.143 cm, the actual value of the edge distance was used for a_{0s}. These values were derived from the test data for case 7 and a_{0s} was kept constant thereafter.

In order to estimate the sensitivity of the predicted joint strength p to the assumed value of characteristic dimension a_0, the values of a_{0t}, a_{0c}, and a_{0s} were varied about $\pm25\%$ from their nominal values (0.229,0.622, and 1.143 cm, respectively). The new failure load p_{new} thus obtained for the corresponding value of $a_{0_{new}}$ for the joint studied in case 1 are presented in Fig. 8. The predicted failure loads are quite sensitive to the variation in the assumed value of a_0. However, it is shown later that once these constants have been determined for a given material system, the joint strength in general can be determined quite accurately.

In Table 4 the lowest failure load predicted analytically for each case has been underlined to indicate the failure load and the predicted mode of failure. It is seen that for cases 1, 2, 4, and 7 the analytical predictions for the failure load and mode of failure are in very close agreement with the experimental results, although three different modes of failure are involved for cases 1, 2, 4, and 7. For case 3, the predicted shearout, bearing, and net tension failure loads are very close to each other, and the experimental data indicate a combined shearout and bearing type failure at a load which is about 10% lower than the predicted load. Similarly for case 5 the combination of net tension and shearout modes of failure was displayed experimentally and the failure load for these modes of failure are fairly close to each other, as indicated by the analytical predictions. For case 6 the magnitude of the predicted failure load differs by about 15% from experimental data but the failure mode is the same. The difference may possibly be due to the use of the maximum strain theory to predict the unnotched laminate strength.

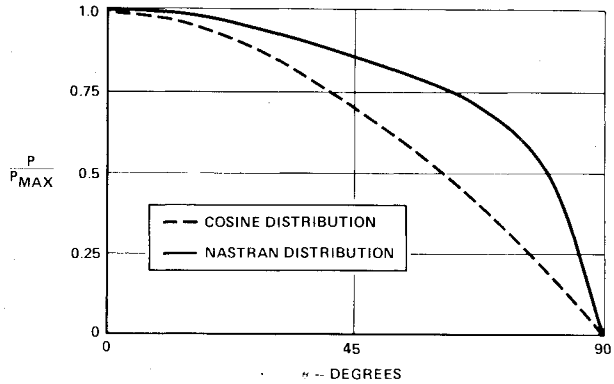
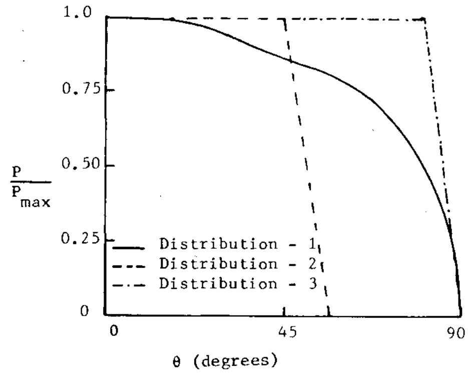


Fig. 5 Radial load distribution.



Radial Load Distribution (N)	1	2	3
Net Tension Failure Load	4928	4408	5151
Bearing Failure Load	5685	3800	5284
Shearout Failure Load	5209	5551	5071

Fig. 6 Effect of varying radial load distribution on predicted joint strength for case 1.

Case 8 in which the laminate is made of only $\pm45°$ laminate shows considerably higher strength and slightly different modes of failure than predicted analytically. It is noted that maximum strain theory indicates that laminate under tension will fail due to shear cracking of the matrix along the 45 deg direction. Since the laminate does not fail across the net section, it is not quite clear how the average stress criterion can be used to predict such modes of failure. However, the predicted strength based upon the present method is conservative.

In case 9 which consists of 0 and 90° laminate only, the mode of predicted and experimental failure is shearout. However, the experimental failure load is considerably higher than the predicted load. It should be noted that the present analysis is linear but the shear stress–strain curve for a 0/90°-laminate shows a considerable amount of nonlinearity and the ultimate shear strain is about twice as large as the proportional limit strain. Since the yielding of the material will allow additional loads to be transferred through the joint, the lower predicted shear load based upon linear theory seems reasonable.

For case 10 the joint fails in a combination of bearing and shearout modes of failure. The analytical predictions show the joint to be critical in the shearout mode of failure, but the bearing failure load is also fairly close to shearout failure load. Usually bearing and shearout modes will tend to interact with each other because the joint does not fail completely during bearing failure.

The results in Table 4 generally indicate slightly higher predicted bearing strengths than those observed ex-

Table 4 Comparison of analytical and experimental data

Case No.	Mode of failure[a]	Experimental results (Ref. 4) Failure load, N High	Low	Average	Present analytical results Bearing failure load, N	Net tension failure load, N	Shearout failure load, N
1	NT	5093	4848	4982	5685	*4928*	5209
2	B	5738	4537	5137	*5204*	5636	5373
3	SO/B	5062	4470	4804	5622	5306	*5222*
4	SO	4537	4092	4226	6739	4630	*4226*
5	NT/SO	8985	7695	8562	14357	9230	10141
6	NT	7651	7250	7517	8602	6476	9901
7	SO	6339	5827	6094	8193	8198	*6094*
8	NT*	4092	3803	3914	5782	*1979*	10230
9	SO	3372	2491	3002	5280	6018	*1726*
10	B/SO	4372	4355	4363	5880	6983	5249

[a] B = bearing failure, NT = net tension failure, SO = shearout failure, NT* = tearout at ±45 deg.

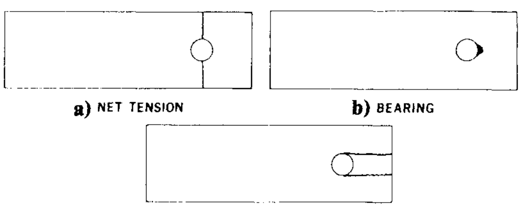


Fig. 7 Different failure modes.

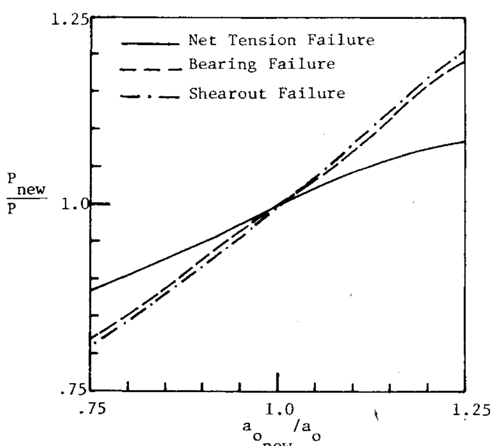


Fig. 8 Sensitivity of predicted joint strength to variation in assumed value of a_0.

perimentally. The predicted bearing strengths in the present analysis are based upon the assumption that a_{0c} for the present material system (T300/SP286) is the same as that used in Ref. 8 for a different graphite/epoxy material system. A lower value of a_{0c} would probably improve the analytical correlation of the experimental data significantly. However, the value used ($a_{0c} = 0.622$ cm) results in satisfactory correlation of analytical and experimental data.

Conclusions

A method for predicting the failure strength and mode of failure for single-fastener composite bolted joints has been presented. Net tension, bearing, and shearout modes of failure have been successfully predicted for various laminate configurations. However, for laminates exhibiting a significant amount of nonlinearity in their stress-strain behavior, the analytical results for the failure load are conservative. It has been shown that the use of the maximum strain theory to predict unnotched laminate strength works quite well in conjunction with the average strain failure criterion to predict joint strength. Although the analytical approach presented in this paper has been demonstrated to be applicable for single-fastener joints, this approach should be equally applicable to predict the laminate failure in the neighborhood of each individual fastener hole of a multifastener joint, provided the stress distribution in such a joint can be determined either analytically or experimentally.

In the present study, the average distances for net tension (a_{0t}), bearing (a_{0c}), and shearout (a_{0s}) modes of failure were kept constant throughout the investigation and the distances a_{0t} and a_{0c} for net tension and bearing modes of failure, respectively, were the same as used in Ref. 8. The distance for the shearout mode of failure (a_{0s}) was calculated from the experimental data for the case in which the failure mode was shearout. The average distances for net tension, bearing, and shearout should be relatively constant for similar graphite/epoxy systems. However, the new values of these constants may have to be determined from experimental data for a new material system.

The use of the average-stress failure criterion has been demonstrated on a small scale using existing experimental data for simple composite joints. The method should be further investigated for complex joints where fastener bending, shearing, and cocking become significant. Also, in the present investigation the fastener size was fixed. The applicability of this approach to different fastener diameters should be explored. Finally, the loading in the present study was uniaxial tension. In future studies other loading conditions such as shear and multidirectional loadings should be investigated.

Acknowledgment

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