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Richard M. Christensen, Steven J. DeTeresa

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DELAMINATION FAILURE INVESTIGATION FOR OUT-OF-PLANE LOADING IN LAMINATES

Richard M. Christensen* and Steven J. DeTeresa
University of California
Lawrence Livermore National Laboratory
Livermore, CA 94550
and
**Stanford University*
Stanford, CA 94305

ABSTRACT: In contrast to failure approaches at the lamina level or the micromechanics level the present work concerns failure characterization at the laminate level. Specifically, attention is given to the ultimate failure characterization for quasi-isotropic laminates. This is in further contrast to the commonly used approaches for initial damage or progressive damage. It is shown that the analytical failure forms decompose into two modes, one for out of plane, delamination type failure and one for in plane, fiber controlled type failure. The work here is mainly given over to the delamination mode of failure. Experimental results are presented for laminates in this mode of failure. These results are then integrated with the analytical forms to give a simple criterion for delamination failure.

KEYWORDS: delamination failure, failure criterion, quasi-isotropic laminates

INTRODUCTION

The present work is concerned with developing a delamination failure criterion for laminates. The quality of a laminate is no better than the capability of the interface between lamina to transmit and transfer loads between adjacent lamina. Significant delamination can completely compromise the laminate load bearing function even though the integrity of the individual lamina remains intact.

The significance of the lamina-to-lamina interface arises in laminates with individual lamina of various orientations. In a degree of anisotropy sense, there are two limiting cases for laminate types. With all the lamina aligned, this is simply the case of the much-studied aligned fiber composite. The other limiting case is the quasi-isotropic laminate. Laminate behavior has usually been approached through an understanding of the behavior of the individual lamina of which it is comprised. The individual lamina is the basic aligned fiber composite. Typical failure criteria for aligned fiber composites are those of Tsai-Wu [1], Hashin [2], Puck [3], and Christensen [4,5]. Many more criteria have been considered in the recent failure examination of Hinton, et al [6].

The usual approach in predicting laminate failure is to start with a particular lamina level failure theory, and then employ a particular cumulative damage procedure to approach the failure state of the laminate. Nowhere

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in any of the procedures does a criterion for delamination emerge. Delamination is usually considered to be an auxiliary condition to be specified independently. The present approach proceeds otherwise, considering delamination to be a central part of any laminate criterion.

It is convenient to approach a delamination criterion through the quasi-isotropic laminate. This is not just because this construction is a logical limiting case, as described above, but also because it is the most widely used single type of composite laminate. The quasi-isotropic laminate form deserves special attention; much of what can be learned from this special case can be carried over to the more complex laminates.

In the next section a general three-dimensional failure criterion will be developed for quasi-isotropic laminates. It will be shown to decompose naturally into two parts, an out-of-plane delamination criterion, and an in-plane failure criterion. Then the delamination criterion will be further developed. Finally, the delamination criterion will be evaluated with experimental data.

QUASI-ISOTROPIC LAMINATE FAILURE CRITERIA

Consider a quasi-isotropic layup for a laminate. Take the 1,2 axes in the plane of the laminate as shown in Fig. 1. For isotropy in the 1,2 plane, then direction 3 is the axis of symmetry. The axis of symmetry x_3 for the laminate should not be confused with the usual treatment of an aligned fiber lamina where x_1 is usually the axis of symmetry.

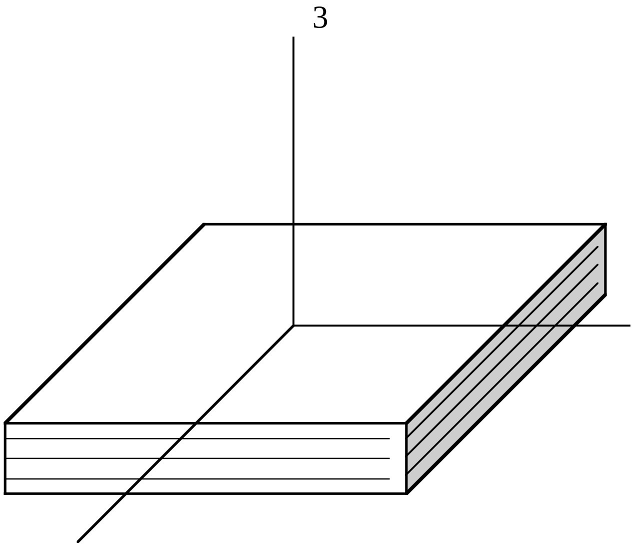

Fig 1. Coordinates for composite laminate.

Relative to a condition of transverse isotropy with x_3 as the axis of symmetry, the invariants of the stress tensor to second degree involve the terms

$$\sigma_{33}\,,\ \sigma_{ii}\,,\ \sigma_{33}^2\,,\ \sigma_{ii}^2\,,\ \sigma_{33}\sigma_{ii}\,,\ \sigma_{i3}\sigma_{i3}\,,\ \sigma_{ij}\sigma_{ij}\,,\qquad i,j=1,2 \tag{1}$$

For quasi-isotropic laminates there are typically two modes of failure:

In-plane fiber controlled
Out-of-plane delamination

Assume that the delamination case occurs at much lower stress levels than the in-plane failures. This effectively decouples the three-dimensional failure into the above two modes of failure.

For the delamination failure mode, take the normal and shear tractions across the interfaces between the lamina, which are

$$\sigma_{23}, \ \sigma_{31}, \ and \ \sigma_{33}$$

Now take only the terms in (1) involving these stresses as forming the delamination failure criterion

$$a\sigma_{33} + b\sigma_{33}^{2} + c\sigma_{i3}\sigma_{i3} \le 1, \qquad i, j = 1, 2 \tag{2}$$

For the in-plane failure mode, take the remaining terms in (1) which are not in the delamination criterion (2), thus

$$d\sigma_{ii} + e\sigma_{ii}\sigma_{33} + f\sigma_{ii}^{2} + g\sigma_{ij}\sigma_{ij} \le 1, \qquad i, j = 1, 2 \tag{3}$$

Relation (3) then is the in-plane fiber controlled mode of failure.

Parameters a, b, c, d, e, f, and g in (2) and (3) are to be determined from experimental data. The delamination criterion (2) will be further developed next. The in-plane failure criterion (3) will be developed in future work.

DELAMINATION FAILURE CRITERION

The delamination criterion (2) with vanishing shear stresses is

$$a\sigma_{33} + b\sigma_{33}^{2} \le 1 \tag{4}$$

The roots are to be determined from the equation

$$b\sigma_{33}^{2} + a\sigma_{33} - 1 = 0 \tag{5}$$

Depending upon the values and signs of a and b in (5) there are several possibilities for the character of the roots for σ_{33}, namely

1 positive and 1 negative root
2 positive roots
2 negative roots
1 negative root
1 positive root
complex conjugate roots

Taking any possible compressive root to be very large in magnitude compared with the tensile root, then the only physically realistic case is that of the 1 positive root, which occurs for

$$\begin{aligned} a &> 0 \\ b &= 0 \end{aligned} \tag{6}$$

With the result (6), the full delamination criterion (2) becomes

$$a\sigma_{33} + c\sigma_{i3}\sigma_{i3} \le 1, \qquad i = 1,2 \tag{7}$$

The parameters a and c are evaluated from the transverse tensile failure value, T, and the shear failure, S, to give (7) as

$$\frac{\sigma_{33}}{T} + \frac{\sigma_{i3}\sigma_{i3}}{S^2} \le 1, \qquad i = 1,2 \tag{8}$$

Finally, writing out the tensor form gives

$$\frac{\sigma_{33}}{T} + \frac{\sigma_{23}^2 + \sigma_{13}^2}{S^2} \le 1 \tag{9}$$

Now take $\sigma_{23} = 0$ leaving the combination of transverse normal stress and one component of shear stress,

$$\frac{\sigma_{33}}{T} + \frac{\sigma_{13}^2}{S^2} \le 1 \tag{10}$$

At failure, take the derivative of (10) with respect to σ_{33} to get

$$\frac{1}{T} + \frac{2\sigma_{13}}{S^2}\frac{d\sigma_{13}}{d\sigma_{33}} = 0 \tag{11}$$

For small σ_{33} then $\sigma_{13} = S$ to give (11) as

$$\left.\frac{d\sigma_{13}}{d\sigma_{33}}\right|_{\sigma_{33}=0} = -\frac{S}{2T} \tag{12}$$

Rewrite this in terms of transverse pressure, $\sigma_{33} = -p$ to get

$$\left.\frac{d\sigma_{13}}{dp}\right|_{p=0} = \frac{S}{2T} \tag{13}$$

This result shows that the shear stress at failure is increased by the presence of pressure, as shown in (13). Conversely, a small transverse tension decreases the shear stress at failure. The overall interaction of transverse normal stress and shear stress causing delamination is given by the full criterion (9).

EXPERIMENTAL

The delamination failure criterion (9) can be compared to results obtained by DeTeresa, et al [7] for the effect of transverse pressure on the interlaminar shear strength of quasi-isotropic laminates. For these tests, specimens having a hollow cylindrical gage section and square ends were machined from a thick laminate panel such that the axis of the cylindrical gage section was aligned with the thickness direction of the panel. Although several composite materials were tested, only one quasi-isotropic laminate of the type $[45/0/-45/90]_{XS}$ was included in the study. This laminate was manufactured using T300 carbon fiber and F584 epoxy matrix (both from Hexcel Corp., Dublin, CA). Tests were conducted using a servohydraulic biaxial test machine (MTS, St. Paul, MN) to control a constant (through-thickness) compressive force while applying a linearly increasing torque to failure. The observed effects of transverse pressure were significant increases in the interlaminar shear strength and ductility. The increase in shear strength with compression is shown in Fig. 2, which confirms the trend predicted by the derived result (13).

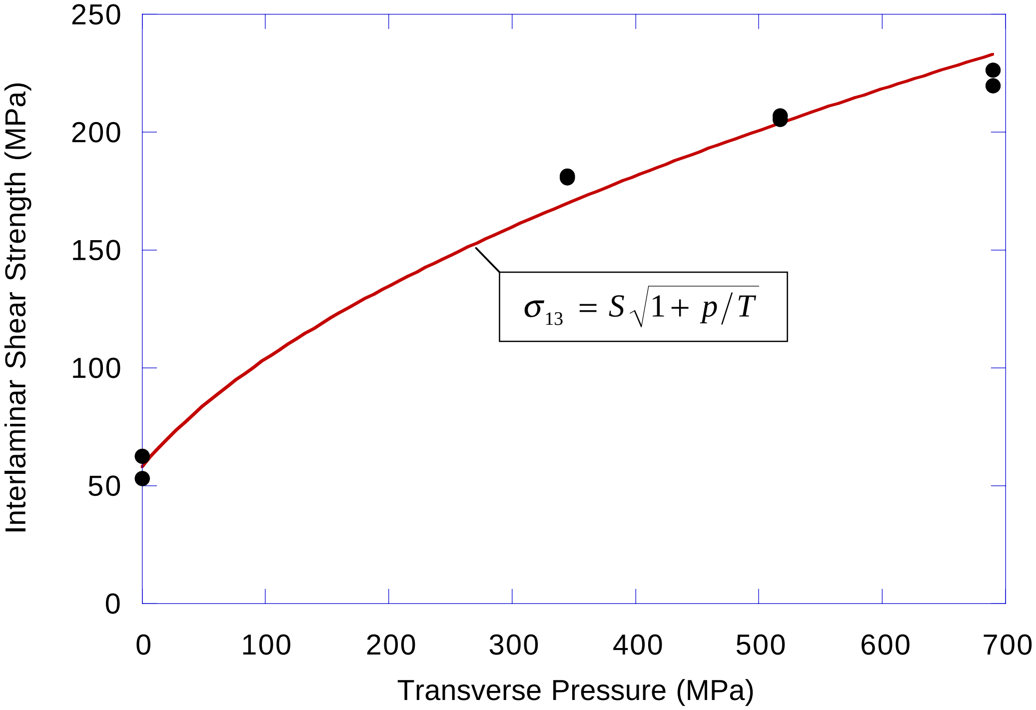

Fig 2. Effect of transverse pressure on interlaminar shear strength of a quasi-isotropic laminate of T300/F584 [7].

To apply the delamination criterion, values of interlaminar shear strength S and delamination tensile strength T are required. The tensile strength was not measured in the study, but can be estimated using the transverse tensile strength of the unidirectional lamina. Alternatively, the data shown in Fig 2 can be fitted using (9) to determine a value of delamination tensile strength. The latter approach was taken and the form shown in Fig. 2 is a best nonlinear fit to the data. This fit yields a value for the delamination tensile strength of 45.4 MPa, which compares favorably with the reported transverse tensile strength of 42.9 MPa [8]. The comparison with experimental results in Fig.2 also shows that the proposed delamination theory predicts the observed nonlinear increase of interlaminar strength with transverse pressure.

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