Strength Design Criteria for Carbon/Epoxy Pressure Vessels

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Pressure vessels made from advanced composite materials are used in a number of sophisticated and strength-critical designs, such as rocket motor cases among other applications. However failure criteria for fiber composite structures are not completely understood. Previous investigations of failure of general carbon/epoxy laminates using a laboratory biaxial test apparatus have shown that fiber direction normal stress or strain can be used as a failure criterion for tension loads, independent of the state of stress. The results of recent biaxial tests on pressure vessel layups are analyzed and shown to be consistent with the previous work. This indicates that carbon/epoxy pressure vessels can be designed using either fiber direction normal stress or strain as a failure criterion, the same failure criteria that are applicable to more general carbon/epoxy laminates.

Introduction

FILAMENT wound pressure vessels made from advanced composite materials have been widely used for their superior strength-to-weight ratios in a number of applications. Typical examples are pressurized gas bottles and solid propellant rocket motor cases. The design of pressure vessels with high performance requirements is quite sophisticated and involves advanced materials and specialized designs. However, it can safely be said that not all aspects of the design process are fully understood.

One key part of the design process that has not been fully understood is that of a suitable failure criterion to be used for predicting ultimate failure. Two aspects associated with the prediction of failure are the statistical variation inherent in the failure loads and the effect of multiaxial stresses on the ultimate failure strengths.

The statistical variation of failure strength is postulated on a micromechanical basis to result from a sensitivity to defects in the individual fibers.[1] It is often also postulated that this will lead to a size effect,[2-8] due to the increased statistical likelihood of more severe defects occurring with larger volumes of material. The studies of the micromechanical aspects of failure play an important role in obtaining a general understanding of the failure process and will undoubtedly contribute to improvements in materials and structures. However, it is difficult to obtain quantitative information from these models, although important progress is being made. The failure processes of fibers in a matrix are quite different from that of the dry fibers alone due to the ability of the matrix to bridge around isolated breaks in individual fibers. A consequence of this is that the micromechanical model calculations become much more difficult.[3-5]

The range of volume of stressed material from a laboratory tow-test specimen to a full-scale structure may be very high, exceeding a factor of 10^6 for large rocket motor cases. Measured strengths of these large vessels place bounds on the possible range of size effects. General experience indicates that ultimate failure properties that are dominated by fiber properties are also influenced by the resin matrix employed. If resin system influences (sometimes changed from tow test to full-scale structure) are accounted for, a reduction in apparent strength up to 20% is often (but not always) observed in going from laboratory specimen to full-scale structure[9] for carbon/epoxy rocket motor cases. This strength reduction may be attributed to the possible inherent scale effect associated with the increase of stressed material volume. However, changes in test procedures and manufacturing methods are also possible influences on the apparent change in strength with size.

The second aspect of failure criteria is that of determining the effects of multiaxial stresses on the failure properties. Historically, these effects were typically ignored, and design was based only on the stresses calculated in the direction of the fibers. However, failure criteria for composite structures other than pressure vessels that significantly involve all components of the stresses, rather than just the stresses in the fiber direction, have been developed.[10] Thus the question is open as to just what criterion should be used for strength critical design of pressure vessels, since multiaxial stresses are always involved. It is this aspect of the design process that is addressed in the present paper.

A standard procedure often used historically for strength design of pressure vessels is to calculate fiber stresses in the cylindrical section of the pressure vessel based on netting analysis and then to use a maximum fiber stress as a failure criterion. In burst tests of both full-scale and subscale pressure vessels, it is often observed that the actual stresses in the critical-hoop direction fibers at failure, as calculated by a netting analysis, depend on the layup and in particular the relative ratio of stresses predicted for the helical fibers to that for the hoop fibers. Thus it would appear that a failure criterion based on fiber stress alone is not sufficient and that other factors must be included as well. Thus far the design process is usually based on experience and testing of subscale vessels as well as predicted fiber stress, but a more rational procedure would obviously be helpful.

Recently, the author has been involved with determining failure criteria for more general loadings of carbon/epoxy laminates, using tension-tension and tension-compression biaxial tests.[11-16] The purpose of the present paper is to apply the results of these findings to the analysis of pressure vessels and hopefully to shed new light on the question of appropriate failure criteria for filament-wound pressure vessel design.

In the following, the previous work on failure under general biaxial stress is briefly reviewed. These results are then applied to a number of recent biaxial tests on laminate layups representative of pressure vessels.

Review of Previous Biaxial Test Results

The biaxial test apparatus developed at the University of Utah Mechanics of Composites Laboratory consists of a cylinder loaded with internal pressure and axial tension or compression force. As shown in Fig. 1, the cylinder is approximately 97 mm (3.8 in.) i.d. by 450 mm (17 in.) in length and

Received August 1, 1989; revision received Jan. 6, 1990.

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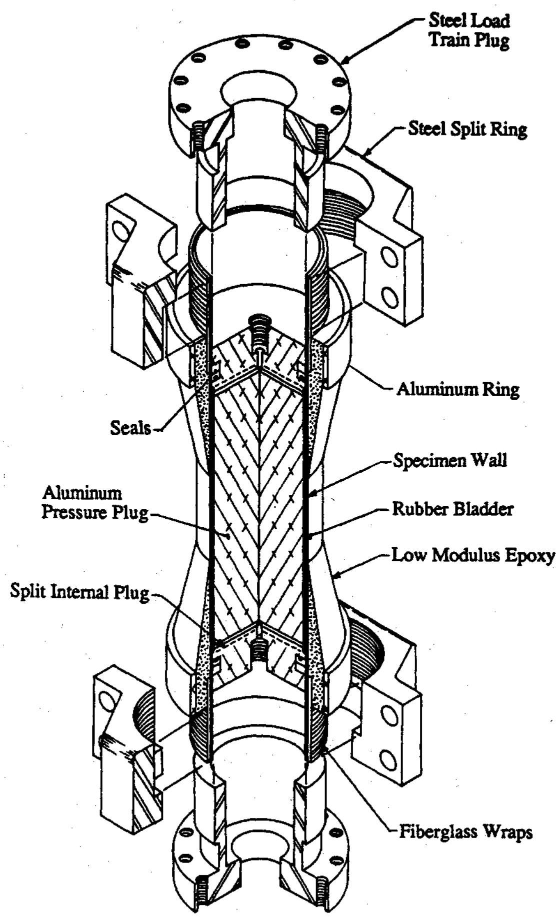

Fig. 1 Tubular specimen for biaxial tests.

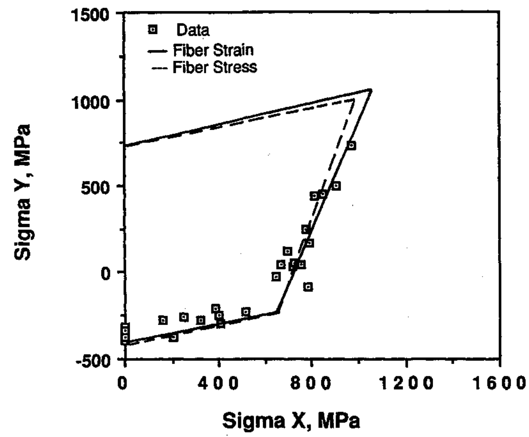

Fig. 2 Ultimate strength of AS4/3501-6 carbon/epoxy [0/ ± 45/90] quasi-isotropic laminates under biaxial stress.

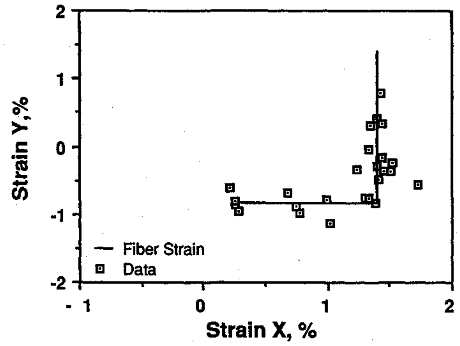

Fig. 3 Maximum fiber direction strains of AS4/3501-6 carbon/epoxy quasi-isotropic laminates under biaxial stress.

is modified by the addition of reinforcement in the end grip and pressure seal region.

As discussed in previous reports on the biaxial results,[11,17] the key to a successful tubular specimen test is the reduction of the stress concentrations that occur in the end grip and seal region of an unreinforced tube. Various previous approaches have been tried,[18-22] but the problem has proved to be somewhat difficult. The approach shown in Fig. 1 includes the use of fiberglass doublers, metal rings, and a low modulus epoxy to achieve a gradual reduction of stiffness from the reinforced region into the gauge section. The placement of these components has been determined by means of extensive finite element analyses and appears to have achieved the objective of minimizing the stress concentrations in the specimen.

Typical results are those shown in Fig. 2, taken from Swanson and Nelson,[14] where the biaxial stresses at failure of a $[0/\pm 45/90]_s$ quasi-isotropic AS4/3501-6 carbon/epoxy laminate are given. The data shown in this and subsequent figures refer to individual failure points obtained from proportional loading tests at various biaxial ratios of the applied laminate stresses. These results have also been compared with various failure theories for laminates. The failure theories have been computed on a ply-by-ply basis using classical lamination theory (CLT) as well as a nonlinear progressive failure theory. A major finding of this work is that it is necessary to distinguish between fiber and matrix failure, as the consequences for ultimate laminate failure are vastly different; that is, matrix failure routinely occurs well before ultimate laminate failure in typical carbon/epoxy laminates. However in so-called "fiber dominated" laminates and loadings, fiber failure coincides with the ultimate failure of the laminate. Although matrix failure in the individual plies of the laminate can be predicted by the various polynomial stress expressions,[23] these expressions are not as successful in predicting ultimate laminate failure. On the other hand, the failure of fibers can be accurately predicted by using either a maximum fiber direction normal stress or maximum fiber direction strain criterion. These fiber (and thus ultimate laminate) failure criteria are also illustrated in Fig. 2.

The results show that either maximum fiber direction stress or maximum fiber direction strain can correlate the experimental failure data quite well. Perhaps surprisingly, the difference between these two criteria is quite small and is essentially indistinguishable experimentally. The reason for the small difference between these two criteria is clearly related to the low value of the Poisson's ratio ν_{21}, which is on the order of 0.025 for an orthotropic carbon/epoxy ply. A plot of the strains at failure as a function of the ratio of applied laminate stresses is shown in Fig. 3. The strains at failure are essentially independent of the applied stresses. The critical fiber direction stress or strain in compression is significantly lower than in tension.

Tests have also been performed on a $[0/\pm 60/\bar{0}]_s$ layup using the biaxial cylinder test.[16] The results are shown in Fig. 4 in terms of laminate stresses. The strains at failure are shown in Fig. 5 as a function of the ratio of applied stresses. As with the quasi-isotropic laminates, no significant effect of the ratio of applied stresses on the strains at failure can be seen.

The major conclusion to be drawn from the previous work with the biaxial cylinder test is that either a maximum fiber direction stress or strain can be used as a criterion for laminate failure over a wide range of applied stresses.

Application to Pressure Vessel Burst Tests

The pressure vessels under consideration are designed with helical layers consisting of $\pm\alpha$ windings and 90 deg hoop windings, where the angles are measured with respect to the

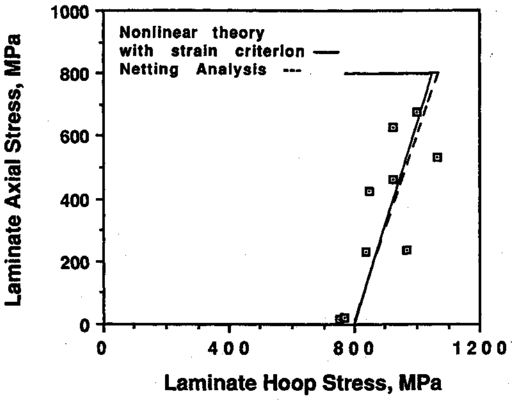

Fig. 4 Ultimate strength of AS4/3401-6 carbon/epoxy $[0/\pm 60/\bar{0}]_S$ laminates under biaxial stress.

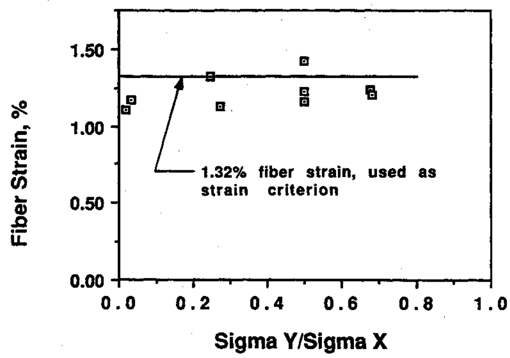

Fig. 5 Maximum fiber direction strains of AS4/3501-6 carbon/epoxy $[0/\pm 60/\bar{0}]_S$ laminates under biaxial stress.

longitudinal axis of the cylinder. Interpretation of experimental results to determine appropriate failure criteria depends on an analysis of the stresses in the individual plies. The relatively high ratio of radius to thickness usually indicates that thick-walled cylinder effects, as described by Lekhnitskii,[24] are not important. Three different analysis procedures can be considered to relate the stresses in the individual plies to the overall loads. These are netting analysis, classical lamination theory, and nonlinear lamination theories that incorporate continuum damage effects.

Stresses in the helical and hoop direction fibers are often interpreted by means of "netting analysis," in which the effect of the resin is completely neglected. The forces in the fibers are assumed to be entirely in the fiber direction and for the layup considered, can be completely determined from considerations of equilibrium. The resulting equations are well documented and can be expressed as

$$\sigma_\alpha = N_z/(t_\alpha v_f \cos^2\alpha) \quad (1)$$

$$\sigma_\theta = [N_t - N_z \tan^2\alpha]/(t_\theta \, v_f) \quad (2)$$

where t is the total thickness of the layers in the helical (t_α) and hoop (t_θ) directions, N_z and N_t are stress resultants in the axial and hoop directions, respectively, and v_f is the fiber volume fraction. The stresses are based on fiber cross-sectional area.

The usual design practice is to specify the relative amount of fibers in the helical and hoop directions so that the helical fiber stresses are somewhat lower than the hoop fiber stresses. This provides an extra margin of safety for the helical fibers to account for the stress concentrations associated with the dome and dome-to-cylinder junction stresses. This is usually expressed in terms of the ratio of helical-to-hoop fiber stresses. Values of fiber-stress ratio of from 0.6–0.9 are often used in practice, and lower values may be used when special circumstances dictate.

A second procedure commonly used for analysis is CLT. Although well documented and straightforward in application, this theory has sometimes been criticized on the basis that it ignores the known nonlinearities in fiber-composite laminate stress-strain behavior.

A third category of theories attempts to include these effects. These theories are often described as including "continuum damage" or "progressive failure" effects and typically attempt to include the effects of material damage such as matrix microcracking on the laminate stress-strain behavior.[25,26]

In the present work, a nonlinear lamination theory previously developed by the author is employed.[13] This model includes three sources of nonlinearity in the laminate behavior. The first is the stiffening of carbon fibers with strain in tension. The AS4 carbon fibers used in the experiments display an increase in secant tensile modulus of 12% at failure in tension, relative to the initial modulus. A second source of nonlinearity is the nonlinear shear behavior associated with resin matrix composites, which has been well documented.[27] The third source of nonlinearity is that associated with matrix microcracking. The occurrence of microcracking in the off-axis plies of carbon/epoxy laminates is well known. A number of models have been postulated to describe the reduction of E_{22} and G_{12} with increasing density of microcracks. The details of the crack formation and density are complex, apparently depending on the thickness of the ply groups and the curing stresses as well as the mechanical stresses. The state of cure stress in pressure vessels is more complex than that in flat plates and depends on the details of mold expansion and stiffness. Because of these complexities, less certainty can be given to the nonlinear theories. However, it was shown in Swanson and Christoforou[13] that good agreement could be obtained with measured laminate stress-strain response.

Comparison with Experimental Data

The results shown in Fig. 4 provide an excellent opportunity to compare the various strength theories, in that data are available in which the ratio of applied stresses have been varied without also changing the lamination layup or the manufacturing process. Thus failure criteria can be evaluated with a minimum of complicating factors.

It was pointed out that netting analysis applied to pressure vessel burst tests showed that the failure stress in the hoop fibers depended on the design stress ratio (i.e., the relative amounts of helical and hoop fibers). On the other hand, the biaxial stress tests given above suggest that either fiber stress or strain can be successfully used as a laminate ultimate failure criterion, independent of the lateral stresses and thus independent of the ratio of helical-to-hoop stress ratio. Of course, the tests are somewhat different in that in the biaxial tests, the geometry was kept constant, and the ratio of stresses was varied. In the pressure vessel tests, the overall applied membrane stress ratios are fixed, but the relative fiber geometry was varied.

A comparison of two failure criteria and analysis procedures with the data is shown in Fig. 4. Shown are a critical fiber stress used in conjunction with netting analysis and the nonlinear continuum damage theory used in conjunction with a fiber direction maximum strain failure criterion. The results are perhaps surprising in that both give an excellent fit to the data, although it would obviously be desirable to have more experimental data available. Thus, these data demonstrate that a correction to fiber properties based on the state of stress should not be used. Although not shown, linear lamination theory can also give good correlation to the data if used with a fiber direction strain criterion. In fact, over the range of the experimental data, a netting analysis with a maximum fiber-stress criterion, the linear CLT with a fiber direction strain criterion, and the nonlinear lamination theory with the same fiber strain criterion all give essentially the same results. How-

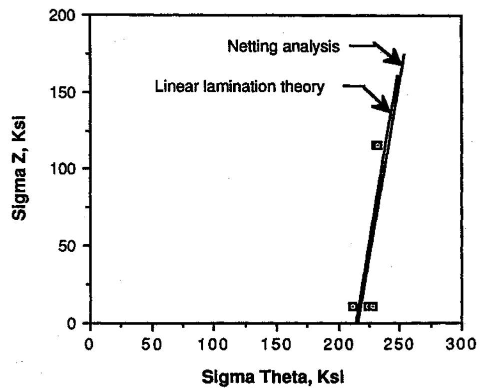

Fig. 6 Comparison of laminate stress predicted by linear lamination theory and critical fiber strain and by a netting analysis with failure data on IM7/55A $[\pm 25/90_2]_S$ carbon/epoxy tubes.

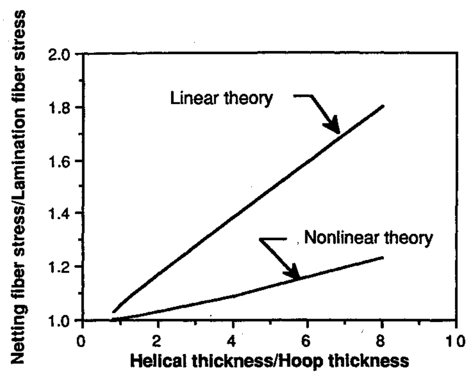

Fig. 7 Comparison of netting and lamination theory analyses for AS4/3501-6 carbon/epoxy $[0_m/(\pm 60)_n]_s$ laminates.

ever, a fiber direction stress criterion cannot be accurately applied with linear lamination theory, as the linear theory does not accurately calculate the fiber direction stresses in the individual plies.

Additional data from pressure burst tests on filament wound tubes of IM7/55A carbon/epoxy with a layup of $[\pm 25/90_2]_s$ are given in Fig. 6. These data are compared with the predictions of both netting analysis and linear lamination theory with a critical fiber strain of 1.76%. Both sets of predictions are essentially equivalent and agree well with the data without any corrections needed for the varying state of stress.

Discussion

The major point addressed in this paper is the apparent discrepancy between the results of pressure vessel tests that show an effect of the state of stress on the apparent fiber strength and the results of biaxial laminate tests that indicate no significant effect of stress state on fiber strength. Mumford et al.[28] report a strong effect of transverse stress on the strength of aramid fiber pressure vessels. It is well known that the aramid fiber has a low transverse strength, and so the result is not surprising. However, the question arises as to whether this same effect will be seen in carbon fiber pressure vessels. The present comparisons with experimental data on failure of cylinder with layups appropriate for pressure vessels in which the applied stress resultants could be varied independently, as shown in Figs. 4 and 6, clearly indicate that the fiber direction stress or strain can be used as a laminate failure criterion, without any correction for the state of stress. Thus, the same failure criteria shown in previous work to be applicable to general "fiber dominated" laminates and loadings are also applicable to pressure vessel layups.

One reason for uncertainty in analyzing pressure vessel tests may lie in the stress analysis of the laminate. It is common practice to use a netting analysis for calculating ply stresses from burst pressures. It is clear that a netting analysis is an approximate theory that would not be expected to be entirely accurate in predicting stresses within a filament wound structure or a laminate. An illustration of this is shown in Fig. 7, where the results of calculations of the stress in the hoop fibers of a $[0_m/(\pm 60)_n]$ laminate are compared for both linear and nonlinear lamination analysis vs netting analysis. The ordinate of this figure is the ratio of stresses calculated by netting analysis to that calculated by either linear or nonlinear lamination theory. The results show that for n approximately equal to m, as used in the experiments, there is not much difference between the analysis methods. However, for n much larger than m, there is a large difference. The netting analysis shows a significant difference relative to the nonlinear lamination analysis, and netting theory becomes increasingly less accurate as the relative number of plies in the hoop and helical directions become unequal. It may also be seen that the netting analysis shows an even larger discrepancy with respect to linear lamination theory. It is believed that, as discussed previously, linear lamination theory is also inaccurate at the higher stress levels near failure that are used in Fig. 7.

It should be noted that the present experiments were carried out for a geometry where the netting analysis is reasonably accurate and did not show any effect of fiber-stress ratio on the fiber-failure stresses. The previous literature results varied the fiber-stress ratio by varying the laminate layup and thus possibly confused the inaccuracy of netting analysis with changes in fiber strength.

It should be noted that the maximum fiber direction stress or strain values that are measured in the laminate tests are somewhat lower than the values measured in unidirectional coupon or tow tests. This difference appears to be about 5% for the AS4/3501-6 carbon/epoxy system and also appears to be independent of the layup. An approximately 20% reduction from coupon to laminate was observed in tests of an IM7/8551-7 carbon/epoxy system.[29]

It is worth noting again that linear lamination theory can give a good prediction for ultimate laminate failure if fiber direction strain is used as a failure criterion but is less accurate if fiber direction stress is used. This is due to compensating errors in the linear theory. That is, in reality the carbon fibers stiffen with tensile strain, whereas the transverse properties that affect the overall laminate stiffness tend to soften. Thus the overall laminate stress-strain response tends to be reasonably well predicted by linear lamination theory, whereas the stress distribution within the individual plies is not as well described.

It is also worth commenting on the preceding results in the context of a general application of failure criteria for continuous fiber laminates. It seems clear from the data presented here that ultimate laminate failure can be well described by a fiber direction stress or strain criterion. The various stress interaction theories for orthotropic materials that have been postulated in the literature in general incorporate various transverse stress effects. These criteria in general do not discriminate between matrix and fiber failure and thus have limited applicability to advanced continuous fiber laminates with characteristic high ratios of fiber to matrix strength.

Summary and Conclusions

The subject of failure criteria suitable for the design of carbon/epoxy fiber composite pressure vessels has been addressed. It has been shown that either fiber direction normal stress or strain can be used as a failure criterion with no correction needed for transverse stress effects. Application to test results on biaxially loaded cylinders with layups appropriate for pressure vessels shows good agreement over a wide range of data. Interpretation of results of pressure vessel tests requires a stress analysis of the laminate to obtain stresses in individual plies. It is shown that netting analysis can vary markedly in accuracy depending on the laminate layup.

Acknowledgments

The assistance of Peter Li and Glenn Colvin in performing some of the experiments is greatly appreciated. Some of the experimental specimens were furnished by Hercules Aerospace, Magna, Utah.

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