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by Travis A. Bogetti, Christopher P. R. Hoppel, Vasyl M. Harik,
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ARL-RP-76 **June 2004**

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14. ABSTRACT

A comprehensive comparison of laminate failure models was established to assess the state-of-the-art in laminate modeling technologies on an international level (known as Worldwide Failure Olympics Exercise) [Compos. Sci. Technol. 58(1998) 1001, 1011, 1225]. In our first contribution to this Exercise (Part A), we presented a complete theoretical description of an analysis methodology and documented predictions for the laminate response and failure behavior of various laminates under a broad range of loading conditions [Compos. Sci. Technol. (in press)]. This report represents our contribution to Part B of the Exercise where the laminate response and failure predictions for 14 different cases are presented and compared with actual experimental test data. The cases include prediction of the effective nonlinear stress vs. strain responses of laminates, as well as, initial and final ply failure envelope predictions under multi-axial loading. Correlation between the theoretical predictions and experimental results are discussed. While reasonable correlation was achieved, the failure analysis employed by the authors was not universally accurate in predicting the laminate failure response for the broad range of test cases considered. This statement, although not surprising, is likely true for any given failure methodology as it is applied to a wide range of laminate lay-ups and loading conditions.

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Predicting the nonlinear response and failure of composite laminates: correlation with experimental results

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Abstract

A comprehensive comparison of laminate failure models was established to assess the state-of-the-art in laminate modeling technologies on an international level (known as the Worldwide Failure Exercise) [Compos. Sci. Technol. 58(1998) 1001,1011,1225]. In our first contribution to this Exercise (Part A), we presented a complete theoretical description of an analysis methodology and documented predictions for the laminate response and failure behavior of various laminates under a broad range of loading conditions [Compos. Sci. Technol. (in press)]. This paper represents our contribution to Part B of the Exercise where the laminate response and failure predictions for fourteen different cases are presented and compared with actual experimental test data. The cases include prediction of the effective nonlinear stress vs. strain responses of laminates, as well as, initial and final ply failure envelope predictions under multi-axial loading. Correlation between the theoretical predictions and experimental results are discussed. While reasonable correlation was achieved, the failure analysis employed by the authors was not universally accurate in predicting the laminate failure response for the broad range of test cases considered. This statement, although not surprising, is likely true for any given failure methodology as it is applied to a wide range of laminate lay-ups and loading conditions.

Keywords: Composite laminate

1. Introduction

In our first contribution to the Worldwide Failure Exercise (Part A), we presented a methodology for predicting the nonlinear stress/strain response and failure behavior of composite laminates [1–4]. The theoretical analysis is an incremental formulation of a well-established three-dimensional laminated media analysis [5,6] coupled with a progressive-ply failure methodology. Nonlinear lamina constitutive relations for the composites are represented using the Ramberg–Osgood equation [7]. Piece-wise linear increments in laminate stress and strain are calculated and superimposed to formulate the overall effective nonlinear response. Individual ply stresses and strains are monitored to calculate instantaneous ply stiffnesses for the incremental solution and to establish ply failure levels. The progressive-ply failure approach allows for stress unloading in a ply and discrimination of the various potential modes of failure.

The aforementioned laminate analysis and progressive ply failure methodology has been programmed into a FORTRAN-based software code entitled LAM3DNL. The LAM3DNL code employs a user-friendly database format for input of laminate architectures, lamina properties, and failure parameters [8]. Output from the code includes the effective laminate stress and strain files as well as a failure assessment summary file that identifies all ply failures that occur during a laminate response prediction program run.

In this paper, we compare our theoretical predictions made in [4] with the experimental data for the fourteen different laminate test cases described by Soden et al. [9]. These test cases have been grouped into three classes (a) biaxial failure envelopes of unidirectional lamina, (b) bidirectional failure envelopes of multidirectional laminates, and (c) stress vs. strain curves of laminates under uniaxial and biaxial loading. For completeness, a summary of the test cases investigated in the paper are presented in Table 1. It is also noted that four different materials were included in the study: (a) E-glass/MY750

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Table 1
Summary of the laminates and loading cases

Loading case	Laminate lay-up	Material	Description of loading cases
1	0	E-glass/LY556/HT907/DY063	Biaxial failure stress envelope under transverse and shear loading (σ_y vs. τ_{xy})
2	0	T300/BSL914C	Biaxial failure stress envelope under longitudinal and shear loading ($\sigma_x$vs.τ_{xy})
3	0	E-glass/MY750/HY917/DY063	Biaxial failure stress envelope under long. and transverse loading ($\sigma_y$vs.σ_x)
4	90/±30/90	E-glass/LY556/HT907/DY063	Biaxial failure stress envelope ($\sigma_y$vs.σ_x)
5	90/±30/90	E-glass/LY556/HT907/DY063	Biaxial failure stress envelope ($\sigma_x$vs.τ_{xy})
6	±55	E-glass/MY750/HY917/DY063	Biaxial failure stress envelope ($\sigma_y$vs.σ_x)
7	0/±45/90	AS4/3501-6	Biaxial failure stress envelope ($\sigma_y$vs.σ_x)
8	0/90	E-glass/MY750/HY917/DY063	Stress–strain curve under uniaxial tensile loading for (σ_y:σ_x = 0:1)
9	±45	E-glass/MY750/HY917/DY063	Stress–strain curves for (σ_y:σ_x = 1:1)
10	±45	E-glass/MY750/HY917/DY063	Stress–strain curves for (σ_y:σ_x = 1:-1)
11	±55	E-glass/MY750/HY917/DY063	Stress–strain curves under uniaxial tensile loading for (σ_y:σ_x = 1:0)
12	±55	E-glass/MY750/HY917/DY063	Stress–strain curves for (σ_y:σ_x = 2:1)
13	0/±45/90	AS4/3501-6	Stress–strain curves under uniaxial tensile loading in y direction (σ_y:σ_x = 1:0)
14	0/±45/90	AS4/3501-6	Stress–strain curves for (σ_y:σ_x = 2:1)

Table 2
Designations for predicted failure modes

Designation	Predicted failure mode
Y1T	Tensile failure in the fiber (1) direction
Y1C	Compressive failure in the fiber (1) direction
Y2T	Tensile failure in the transverse (2) direction
Y2C	Compressive failure in the transverse (2) direction
Y3T	Tensile failure in the through-the-thickness (3) direction
Y3C	Compressive failure in the through-the-thickness (3) direction
Y23	Interlaminar shear in the 23 direction
Y13	Interlaminar shear in the 13 direction
Y12	In-plane shear (12 direction)

epoxy, (b) E-glass/LY556 epoxy, (c) T300 graphite/BSL 914C epoxy, and (d) AS4 graphite/3501-6 epoxy. Correlation between the theoretical predictions and experimental results are discussed for each of the load cases.

2. Correlation of predictions with experimental results

2.1. Loading case 1: biaxial failure envelope of (σ_y vs. τ_{xy}) for [0] E-glass/LY556 epoxy

A comparison of experimental results to theoretical predictions for this load case is presented in Fig. 1. The solid lines represent the predicted failure envelope. The predicted failure modes are indicated in bold print (Y12, Y2C, Y3T, and Y2T); the key for these symbols is given in Table 2. The dotted line on Fig. 1 indicates the predicted initial ply failure for the laminate (transverse tension in the through-the-thickness direction). The solid squares indicate the unidirectional strengths provided in the initial material property input (Table 1 in Ref. [2]), and the open circle indicate the test results.

Reasonable correlation between experimental and theoretical predictions is observed. Key points for comparison are intersections with the load axes. Discrepancy between the transverse compression strength prediction and the test data can be attributed to the transverse compression strength originally provided as input not agreeing with the experimental data obtained to support this portion of the exercise.

There appears to be some degree of interaction between the shear and transverse strengths that is not captured by the maximum strain criteria used in the present analysis. An interactive failure criterion such as Tsai-Wu may be better at capturing the biaxial load failure behavior.

2.2. Loading case 2: biaxial failure envelope of (σ_x vs. τ_{xy}) for [0] T300 graphite/BSL 914C epoxy

A comparison of experimental results to theoretical predictions for this load case is presented in Fig. 2. As with load case 1, reasonable agreement is observed for the biaxial failure envelope. The experimental data and the predictions both show no interaction between the

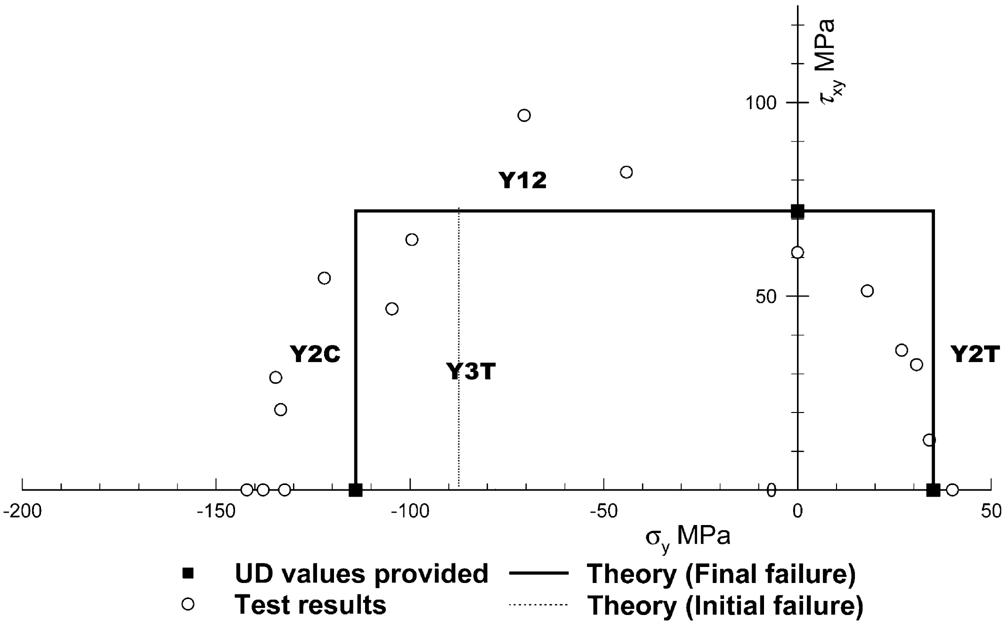

Fig. 1. Biaxial failure stresses for 0° lamina made of GRP material. Material type: E-glass/LY556/HT907/DY063.

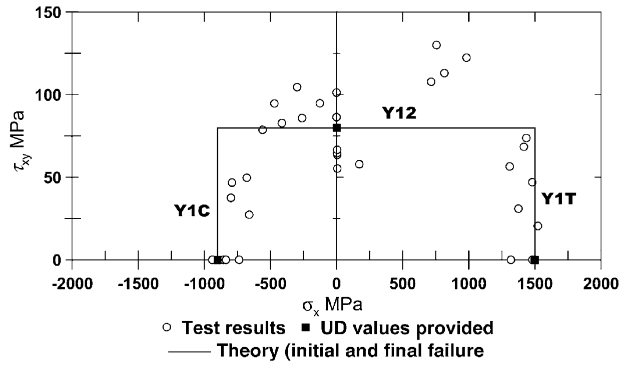

Fig. 2. Biaxial failure stresses for 0° lamina made of CRFP material. Material: T300/914C.

applied shear stress and the fiber direction tensile stress when the predicted failure mode is tensile failure in the fiber direction. When the predicted failure mode is shear dominated (Y12) the experimental data shows potentially some interaction between the stresses that is not predicted by the theory, but it is difficult to draw a conclusion due to the significant scatter in the experimental data, seen especially at $\sigma_x = 0$. When the predicted failure mode is fiber compressive failure (Y1C) there does not appear to be any interaction between the stress fields in the theory or experimental results, although this conclusion is again weakened by the scatter in the data.

2.3. Loading case 3: biaxial failure envelope of (σ_y vs. σ_x) for [0] E-glass/MY750 epoxy

A comparison of experimental results to theoretical predictions for the biaxial failure envelope for this unidirectional laminate is presented in Fig. 3. For the limited amount of test data, good correlation was found for this test case. The theory predicts that while the final tensile and compressive failures in the fiber direction (σ_x) are almost independent of the transverse stress-state, the tensile and compressive failures in the transverse (σ_y) direction are strongly influenced by the axial (σ_x) stress due to the Poisson's effects in the material. The theoretical predictions are found to be consistent with this general trend in the fourth quadrant of the failure envelope. The uniaxial compression strength prediction of $\sigma_1 = 800$ MPa and $\sigma_2 = 0$ MPa is due to a Y3T failure that changes the in-plane behavior of the lamina due to a drop in the transverse and through-the-thickness moduli. The theory over-predicts the transverse

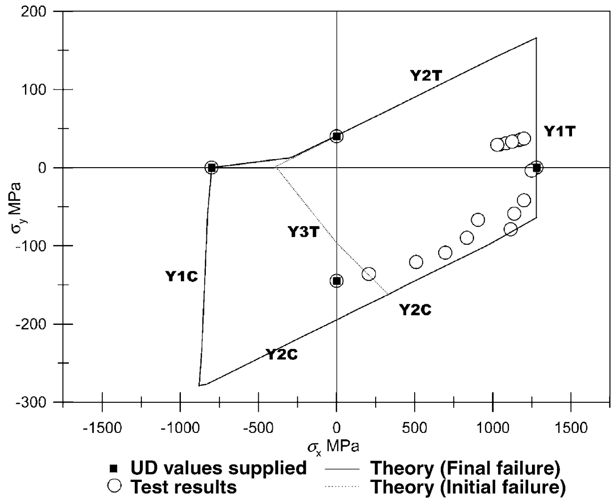

Fig. 3. Biaxial failure envelope of 0° GRP lamina under combined σ_x and σ_y stresses. Material: E-glass/MY750 epoxy.

compressive strength of the laminate (Y2C) because it neglects the nonlinear behavior of the stress–strain curve under transverse compression.

2.4. Loading case 4: biaxial failure envelope of (σ_y vs. σ_x) for [90/+30/−30]s E-glass/LY556 epoxy

A comparison of experimental results to theoretical predictions for this load case is presented in Fig. 4. The theoretical predictions for this load case indicate that multiple ply level failures occur prior to the "final" laminate failure. The first predicted failure modes are indicated by the dotted line in Fig. 4. For the entire biaxial failure envelope, transverse tensile failures (either in the 90° or ±30° layers) are predicted to occur first, followed by catastrophic of "final laminate failure." Overall, the theoretical predictions match well with the test results, with the exception of the predictions made under load combinations involving transverse (σ_y) compression. In this region (second and third quadrants) the predictions of failure overestimate the test results. The test results do not indicate the failure mode or the extent of damage in the specimens. It is also possible that the failure was dominated by the initial transverse tensile failure of the 90° plies.

2.5. Loading case 5: biaxial failure envelope of (σ_x vs. τ_{xy}) for [90/+30/−30]s E-glass/LY556 epoxy

A comparison of experimental results to the theoretical predictions for this load case is presented in Fig. 5. Reasonably good agreement for this load case was achieved except in second quadrant where the predictions somewhat underestimated the test results. In this quadrant, failure is predicted to involve initial transverse tension failure (Y2T) in the −30° plies, followed by longitudinal compression failure (Y1C) in the −30° plies. In the analysis, the transverse tensile properties (modulus and Poisson's ratios) are reduced to very small values when an initial failure is predicted. This approximation may be too severe for these experiments. In experiments, transverse cracking may occur, but it may not be extensive enough to completely reduce the mechanical properties in this direction. Thus, the strength predictions are conservative. In the first quadrant, the predicted strengths are within the scatter of the experimental data.

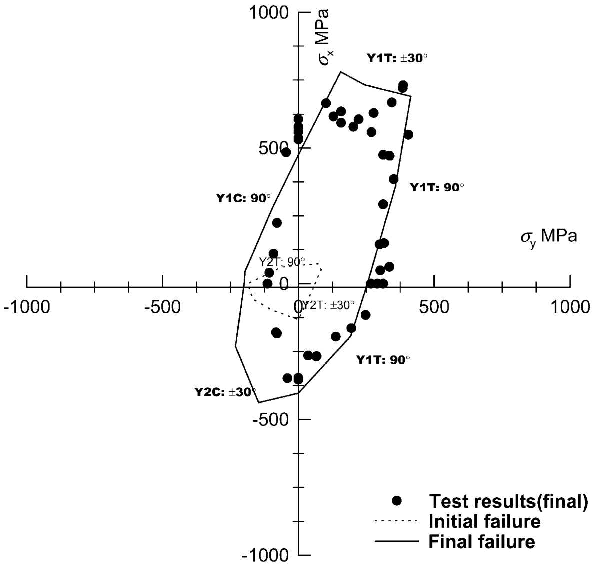

Fig. 4. Biaxial failure envelope for (90°/±30°) laminate under combined σ_x and σ_y stresses. Material: E-glass/LY556 epoxy.

2.6. Loading case 6: biaxial failure envelope of (σ_y vs. σ_x) for [+55/−55]s E-glass/MY750 epoxy

A comparison of experimental results to theoretical predictions for this load case is presented in Fig. 6. The general appearance of the correlation between the predicted strengths and the test results is good. The failure envelope is governed by longitudinal compression strain failure (Y1C) in the third quadrant and by longitudinal tension strain failure (Y1T) in the first quadrant and in-plane shear (Y12) failure in the second and fourth quadrants. In the second, third, and fourth quadrants, the predicted strengths are within the experimental scatter. In the first quadrant, there is considerable variation in the experimental strengths depending on the

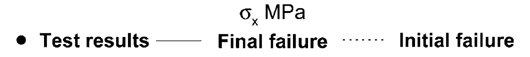

Fig. 5. Biaxial failure stresses for (90°/±30°) laminate under τ_{xy} and σ_x stresses.

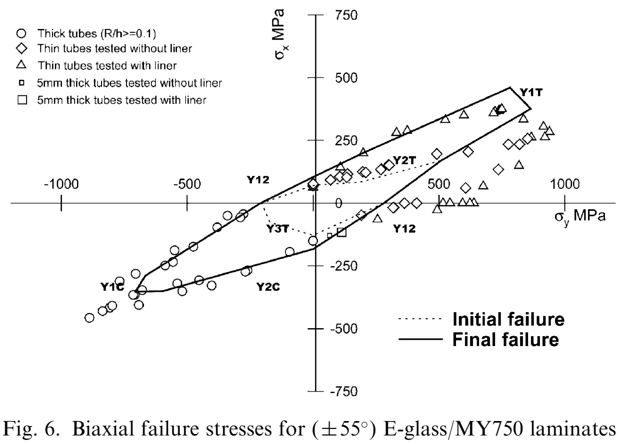

Fig. 6. Biaxial failure stresses for (±55°) E-glass/MY750 laminates.

test specimen geometry. The thin tubes tested without liner give results consistent with the predicted first ply failure (transverse tension or Y2T in the ±55 plies). The thin tubes tested with a liner appear to follow the predictions for a final failure (Y1T) in the ±55 plies. More data on the nature of the experimental failures for each of the different specimens would be helpful in interpreting these results. However, given the biaxial stress state and the predicted multiple failure modes, the predictions show reasonably good agreement with the experimental results. The underprediction of the Y1C failures in the third quadrant could be brought more in line with the experimental data if the through the thickness stresses were taken into account. Consideration of these through thickness stresses would increase the appearant Y1C value of the composite lamina.

2.7. Loading case 7: biaxial failure envelope of (σ_y vs. σ_x) for [0/+45/−45/90]s AS4 graphite/3501-6 epoxy

A comparison of experimental results to the theoretical predictions for this load case is presented in Fig. 7. The predictions show good correlation with the experimental results in the first quadrant where the predicted failure mode is tensile in the fiber direction of the 0 plies and in the fourth quadrant where the predicted failure mode is compressive in the fiber direction of the 90° plies. In the third quadrant, the experimental results appear to match more closely with the predicted initial failure mode (through-the-thickness tensile failure or Y3T) than the predicted final failure mode (Y1C in the 0° or 90° plies). This good correlation is likely coincidental as the model neglects the three dimensional through the thickness stresses due to the externally applied radial pressure. These through the thickness stresses, if taken into account in the predictions, would also alter the location of the Y3T line.

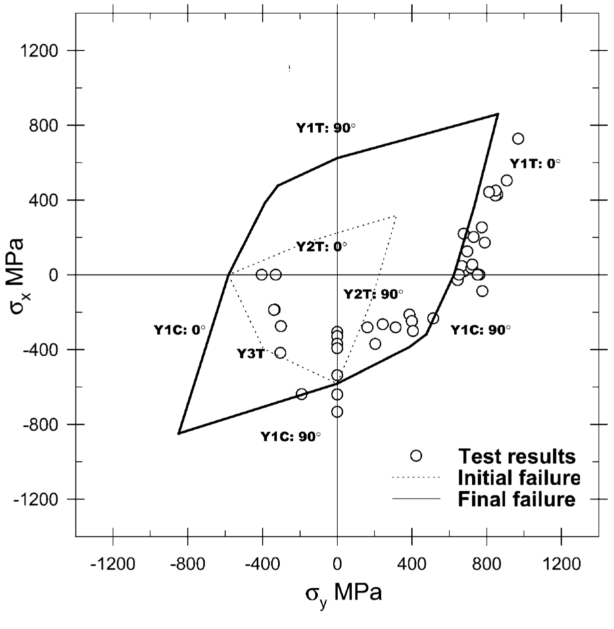

Fig. 7. Biaxial failure stresses for (0°/±45°/90°) AS4/3501-6 laminates.

2.8. Loading case 8: stress–strain curves of (σ_y:σ_x = 0:1) for [0/90]s E-glass/MY750 epoxy

A comparison of experimental results to the theoretical predictions for this load case is presented in Fig. 8. The predictions are in excellent agreement with the test results for this load case. A predicted transverse tensile failure in the 90° plies at $\varepsilon_x = 0.25\%$ is associated with the observed initial cracking point on the stress versus strain curve. In the theoretical model, when the initial transverse tensile failure occurs in the 90 plies, the properties are reduced immediately (thus the sharp drop in the theory). In the experiment, the transverse cracking occurs progressively and the properties are reduced over a larger strain region (thus the theoretical and experimental curves show a slight difference after the initial failure occurs). Although the model does not predict the second observed failure mode of "longitudinal splitting", the ultimate load due to fiber tensile failure in the 0° plies was accurately predicted. The predicted Poisson strains (ε_y) are also in good agreement with the test results.

2.9. Loading case 9: stress–strain curves of (σ_y:σ_x = 1:1) for [+45/−45]s E-glass/MY750 epoxy

A comparison of experimental results to theoretical predictions for this load case is presented in Fig. 9. The theoretical predictions are in good agreement with the test results in the initial loading portion of the stress

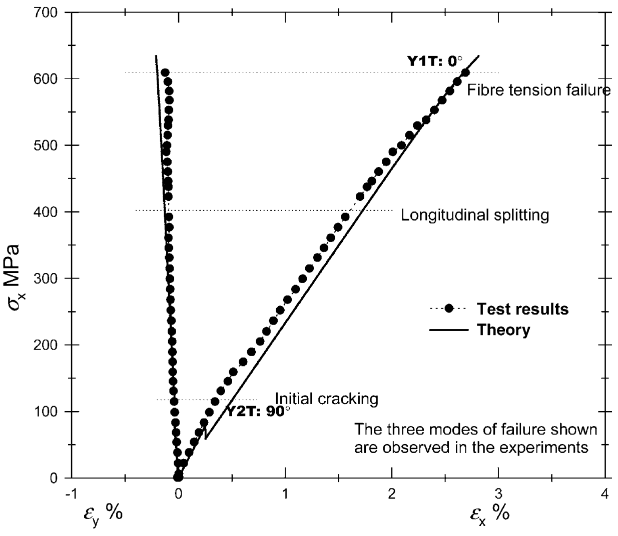

Fig. 8. Stress–strain curves for 0°/90° E-glass/MY750 laminate under uniaxial tension.

versus strain curve. The point where first cracks were observed correlates with the prediction of transverse tensile failure in the ±45° plies. At this point, the model drops the transverse tensile properties, over-predicting the damage in the laminate. The experimental results show a more gradual reduction in properties, showing reasonably good correlation with the theory up until about 2% strain. Beyond this point the analysis predicts a higher stress at ultimate failure (predicted to be tensile failure in the fibers). It is possible that in the experiments the accumulated transverse matrix cracking caused the final failure before the predicted fiber tensile failure could occur.

The following statement applies to load cases 9–12. The over prediction of the stress responses for the laminates could be partially attributable to the fact that the current model does not account for changes in the tubular specimen geometry due to rotation (scissoring) of fibers and due to the radial expansion or contraction in the diameter.

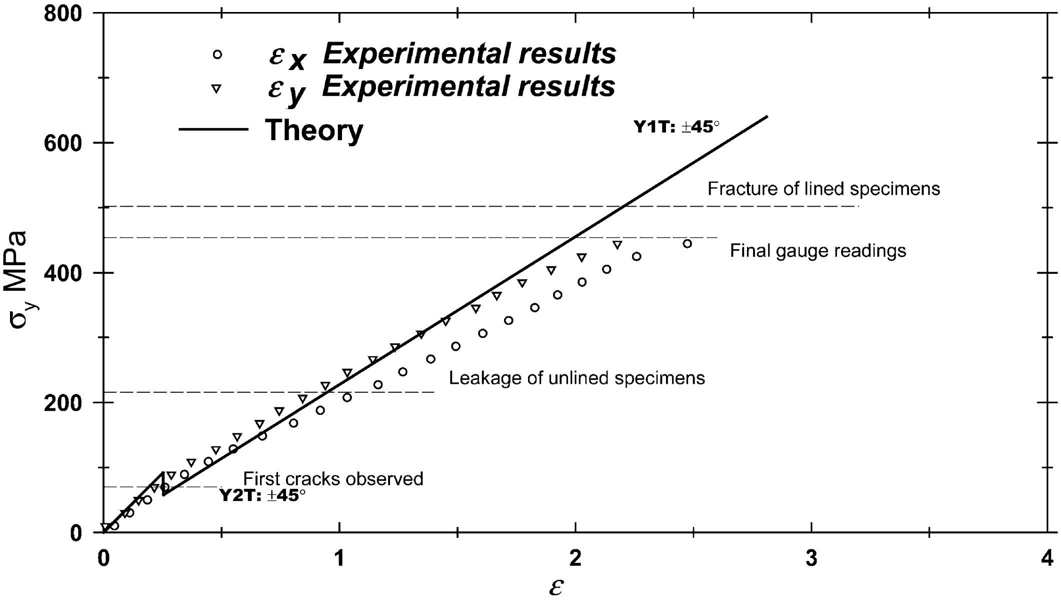

Fig. 9. Stress–strain curves for ±45° E-glass/MY750 laminate under $\Psi/s\xi = 1/1$.

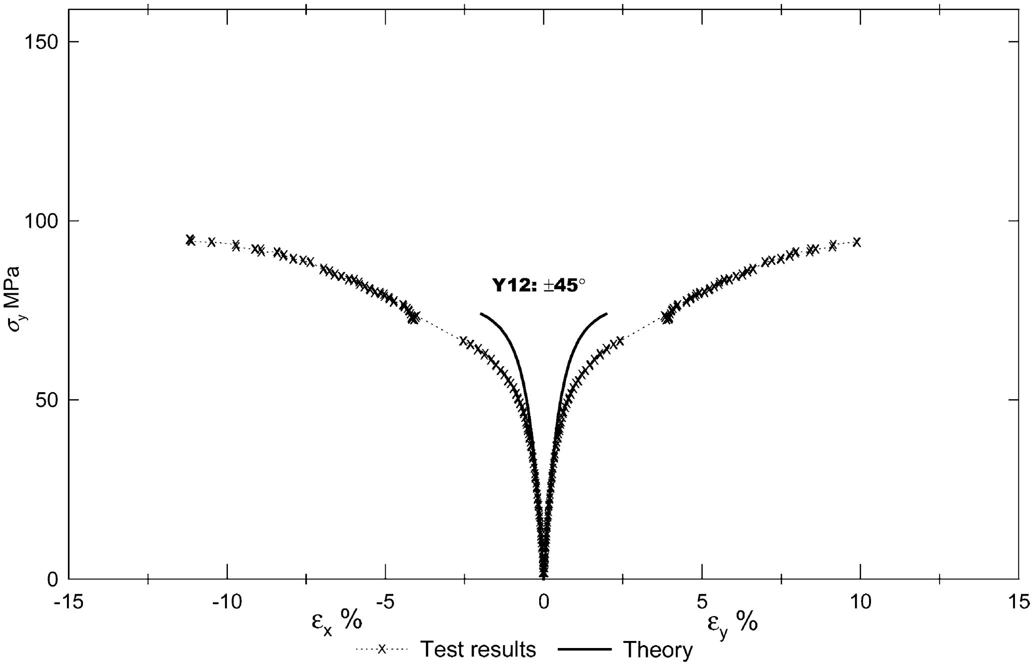

Fig. 10. Stress–strain curves for ±45° E-glass/MY750 laminate ($\sigma_y/\sigma_x = 1/-1$).

2.10. Loading case 10: stress–strain curves of (σ_y:σ_x = 1:-1) for [+45/-45]s E-glass/MY750 epoxy

A comparison of experimental results to the theoretical predictions for this load case is presented in Fig. 10. The initial slope of the stress versus strain predictions matched well with the test results, but the data sets diverge at strains beyond 1% where the predictions are much stiffer than the test results. The predicted ultimate failure strain was far less than the experimental. Again, this large discrepancy between model predictions and the test data could be associated with the fact that the model does not account for fiber rotations and tubular specimen geometry changes.

2.11. Loading case 11: stress–strain curves of (σ_y:σ_x = 1:0) for [+55/−55]s E-glass/MY750 epoxy

A comparison of experimental results to theoretical predictions for this load case is presented in Fig. 11. The predictions of the stress strain response for this load case were in good agreement with the test data up to just over 2% strain, where ultimate laminate failure (shear failure in the ±55° plies, Y12) was predicted. As with the previous load case, the test data indicates that the laminate was able to carry load well beyond the predicted point of ultimate failure. Model predictions for failure are at much lower strain levels than the test date for reasons explained above.

2.12. Loading case 12: stress–strain curves of (σ_y:σ_x = 2:1) for [+55/−55]s E-glass/MY750 epoxy

A comparison of experimental results to theoretical predictions for this load case is presented in Fig. 12. The predictions for the initial portion of both of the stress versus strain responses are in good agreement with the test results. At approximately 150 MPa, a transverse tensile failure (Y2T) is predicted in the ±55 ply. In the model, the properties are reduced immediately. In the experimental results, the transverse damage accumulates in a progressive manner so that the experimental results are initially stiffer, but become more compliant than the predictions. Better correlation with between the predicted and measure response in the tubular specimens could be achieved if the model was modified to account for fiber re-orientation due to large deformation.

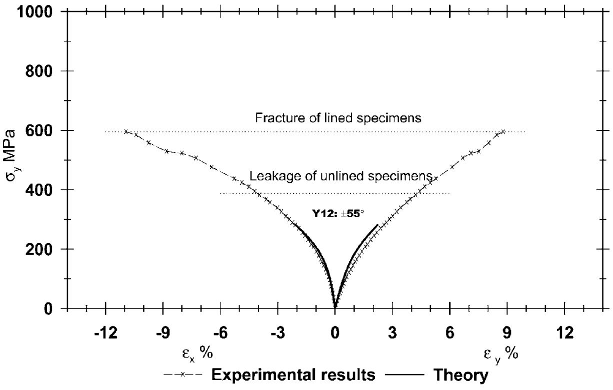

Fig. 11. Stress–strain curves for ±55° GRP laminate under uniaxial tension ($\sigma_y/\sigma_x = 1/0$).

2.13. Loading case 13: stress–strain curves of (σ_y:σ_x = 1:0) for [0/+45/−45/90]s AS4 graphite/3501-6 epoxy.

A comparison of experimental results to theoretical predictions for this load case is presented in Fig. 13. In general, the predictions are in good agreement with the test results for this load case, for both the axial and Poisson strains. At approximately 0.44% strain, transverse tensile failure (Y2T) is predicted in the 90° plies. The experimental results do not show a reduction in properties at this point and therefore appear stiffer for the rest of the stress-strain curve. This difference could again be due to the immediate reduction in properties in the model. In the experiment, transverse cracking may have occurred in a more progressive manner (the experimental curve shows a slight deviation from linear behavior). Not surprisingly, ultimate laminate failure is dominated by longitudinal tension failure in the 0° plies, Y1T.

2.14. Loading case 14: stress–strain curves of (σ_y:σ_x = 2:1) for [0/+45/−45/90]s AS4 graphite/3501-6 epoxy.

A comparison of experimental results to theoretical predictions for this load case is presented in Fig. 14. As

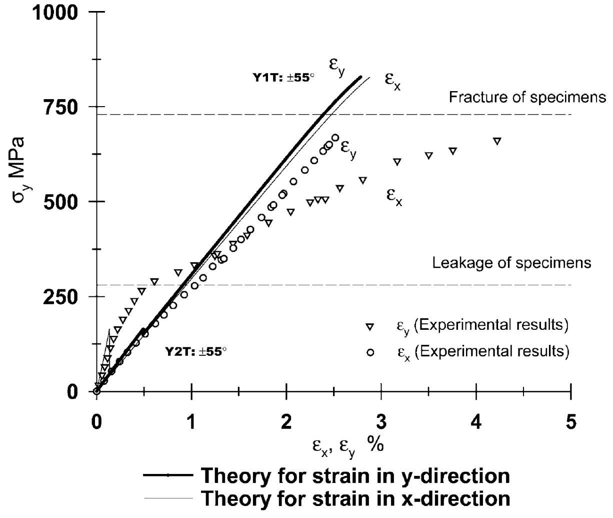

Fig. 12. Stress–strian curves for a ± laminate made of E-glass/MT750 epoxy material under $\sigma_y/\sigma_x = 2/1$.

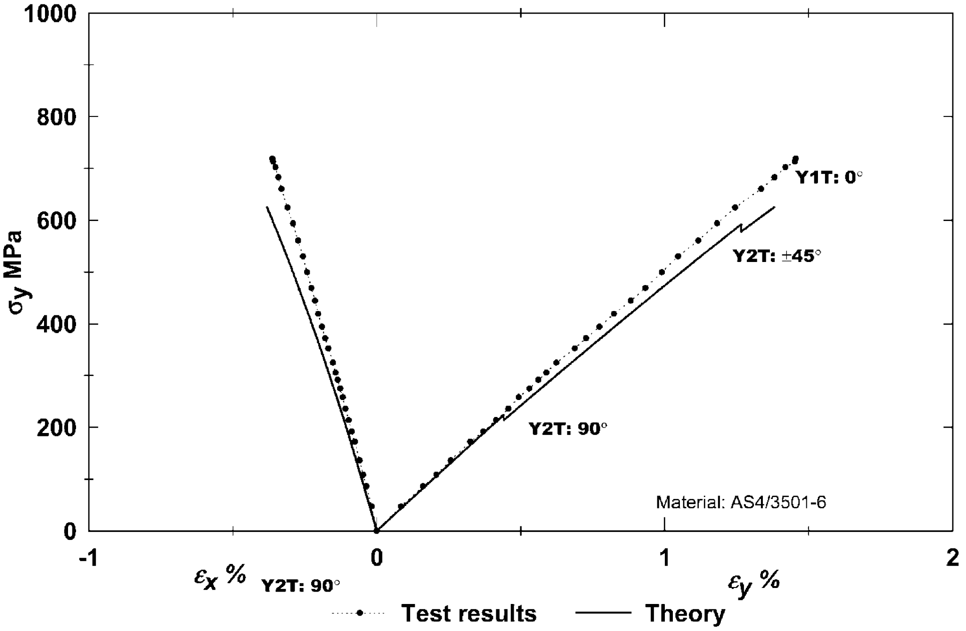

Fig. 13. Stress–strain curves for (0°/±45°/90°) laminate under uniaxial tension ($\sigma_y/\sigma_x = 1/0$).

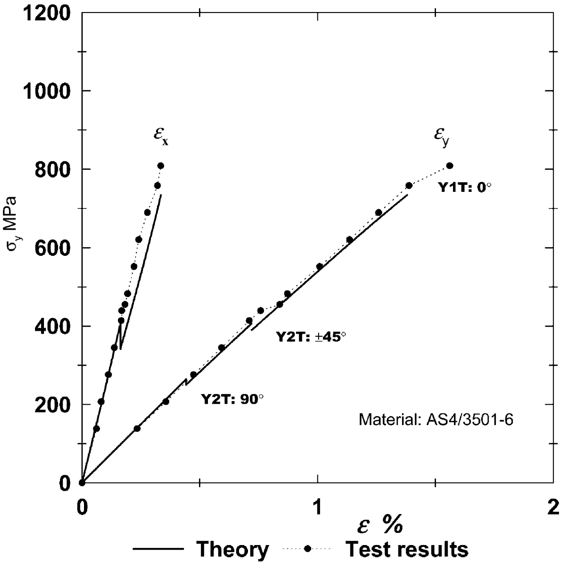

Fig. 14. Stress–strain curves for (0°/±45°/90°) laminate under biaxial stress ($\sigma_y/\sigma_x = 2/1$).

with the previous load case, predictions for the quasi-isotropic graphite composite laminate are in good agreement with the test results. Transverse tensile failure in the 90° plies, Y2T, is predicted early in the load history (about 0.5% strain) and this seems to correlate with the nonlinear softening of the laminate stress strain response. The predicted transverse tensile (Y2T) failure of the ±45 plies occurs at the same location as a load-drop in the experimental results. As in Loading Case 13, ultimate laminate failure is dominated by longitudinal tension failure in the 0° plies, Y1T. The lower predicted failure strength could be due to assuming complete degradation of transverse properties in the 90° and ±45 plies in the model, while experimentally only a partial degradation in properties occurs.

3. Conclusions

Correlation between the theoretical predictions and experimental results were presented and discussed. While reasonable correlation was achieved for most of the case studies, the failure analysis employed by the authors was not universally accurate in predicting the laminate failure response for the broad range of test cases considered. This statement, while not surprising, is likely true for any given failure methodology as it is applied to a wide range of laminate lay-ups and loading conditions. In several cases examined in this exercise, over prediction of the stress responses for the laminates could be partially attributable to the fact that the current model does not account for changes in the tubular specimen geometry due to rotation (scissoring) of fibers and due to the radial expansion or contraction in the diameter. This is one example of the inherent variability or special circumstances that one may encounter in composites modeling that will ultimately contribute to difficulties in consistently correlating theoretical and experimental predictions.

In general, a composite failure model is essentially a combination of assumptions, approximations and physical laws which are made to establish a tractable estimation of composite failure. The relationships between microstructural effects, statistical variations and composite failure are vastly too complex to be completely addressed in the most comprehensive failure model. This is especially true in many of the cases presented in this study where multiple failure modes occur prior to the final laminate failure.

It is the authors' opinions that no truly universal composite laminate failure model or analysis exists. Even the most sophisticated "state-of-the-art" models are not capable of predicting the broad range behavior exhibited under a variety of materials, lay-ups and loading conditions. At best, those failure models that capture the "widest" range of behavior—with reasonable effort—are most valuable as predictive tools. The failure theories used should be relevant and proven within a given application. This is to say that the business of predicting composite laminate failure can perhaps be just as easily viewed from an engineering perspective than it can from a scientific one.

It is worth pointing out that a comparison between the results of the present model and those of other models, employed in the failure exercise, is presented in Ref. [10].

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