EXPERIMENTAL AND NUMERICAL FAILURE PREDICTIONS OF BIAXIALLY-LOADED QUASI-ISOTROPIC CARBON COMPOSITES

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Abstract

Many innovative techniques have been developed over the past several years to predict the failure response of laminated composite materials. Some of these new approaches have been rigorously developed while others have adopted much more of an empirical basis, but few have been validated by multi-axial experimentally-generated data. The general trend for these modeling techniques appears to be towards predicting failure in materials at the micro (fiber and matrix) rather than the macro (lamina or laminate)-level. Through pioneering efforts such as the World Wide Failure Exercise [1], the greater composites community has recently demonstrated the inability to accurately predict the response of composite materials; a limitation which has already, and will continue to, hampered the optimal use of composite materials.

In this study, parallel numerical and experimental approaches were pursued to evaluate the fundamental response of a quasi-isotropic carbon composite laminate when subjected to unidirectional and biaxial loading conditions. The genesis for this study was the simple desire to produce an accurate prediction of a composite's behavior in a structural application using only well-established standard test methods to generate input material properties. Numerically, a micro-level approach, Multi-Continuum Theory (MCT), was used to predict and analyze the onset of damage and ultimate failure of uniaxial and biaxially loaded cruciform test specimens. Uniaxial tests were performed on the same material system to generate input material properties for the MCT analysis. These MCT failure predictions were then validated experimentally using a unique triaxial test facility capable of performing both biaxial (two-dimensional, in-plane) and triaxial (three-dimensional) strength measurements.

1 Background

Like many other researchers, the present authors have engaged in numerous activities that involved the design of composite structures for marine, space, automotive, recreational, and personal use, just to cite a few examples. While these experiences were for significantly different applications in wildly diverse environments, several common themes have emerged as a result of these efforts. First, it is exceedingly difficult to accurately design composite structures because there is no universally accepted and easily implemented analysis technique available to designers. Often the most successful tools available to composite design engineers is intuition and experience. Secondly, obtaining reliable experimental data for composite materials is often exceedingly difficult, if not impossible, for many designers or manufacturers. While this is surely a consequence of the vast amount of unique composite materials and the immaturity of applicable test methods, it is nonetheless a considerable impediment. It is because of these experiences that the authors have dedicated more than a decade of effort into developing unique analysis and testing capabilities. The fundamental questions addressed in the current effort was whether significant differences in failure strength predictions exist when quasi-isotropic carbon composite laminates were modeled as unit cells or as structural members and experimentally whether there was significant correlation between uniaxial and biaxial test results.

In previous studies, a series of a thickness-tapered cruciform specimen configurations have been used to determine the biaxial (two-dimensional, in-plane) and triaxial (three-dimensional) strength of several carbon/epoxy and glass/vinyl-ester laminate configurations [2-7]. Refinements to the cruciform geometry have been shown capable of producing acceptable results for cross-ply laminate configurations. However, the presence of a biaxial strengthening effect in quasi-isotropic, $[(0_N/90_N/\pm45_N)_M]_S$, laminates have brought into question whether the cruciform geometry could be used to successfully generate two-dimensional strength envelopes. In the present study, a two-dimensional failure envelope for an IM7/977-2 carbon/epoxy laminate was developed at the Air Force Research Laboratory, Space Vehicles Directorate, using a triaxial test facility shown in Figure 1. The electromechanical test frame is capable of generating any combination of tensile or compressive stresses in $\sigma_1:\sigma_2:\sigma_3$ stress space and can evaluate the uniaxial (one-dimensional, in-plane), biaxial or triaxial response of composite materials [8]. Results are promising as they indicated that failure in the majority of the IM7/977-2 specimens occurred in the gage section. This leads the authors to believe that maximum biaxial stress states were correctly generated within the test specimen.

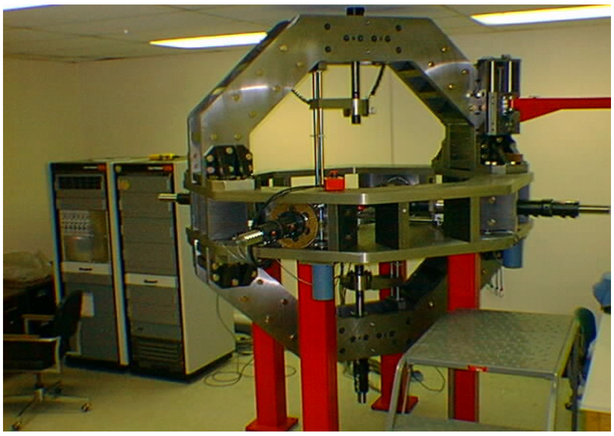

Fig. 1. Triaxial Test Facility at the Air Force Research Laboratory.

However, one aspect of the previous testing that warranted further investigation, and was pursued in the present study, was whether thickness-tapered biaxial cruciform specimens were capable of generating accurate uniaxial data compared to well-established American Society for Testing and Material Standards (ASTM) test methods for uniaxial test specimens. This is not to suggest that the use of thickness-tapered cruciform specimens, as shown in Figure 2, in lieu of ASTM test methods is a prudent venture, but rather that this is a critical aspect of the evolution of multiaxial test methods for composites for two primary reasons. First, the intersection of any failure envelope in 2-D stress space is most easily defined by a uniaxial loading condition; uniaxial tension or compression, for example. For most failure theories, the scale, but not the shape, is defined by the predicted uniaxial strength in both tension and compression, thus the ability of any multiaxial test method to accurately determine this failure point is of paramount importance. Secondly, the performance of any multiaxial test method should generate similar results when operated in a less complicated uniaxial loading condition. Confidence is generated in the evolution of test methods from uniaxial to biaxial loading conditions when these two conditions agree.

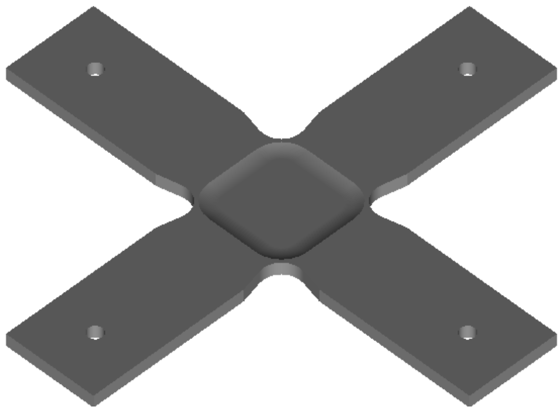

Fig. 2. Thickness-Tapered Cruciform Specimen.

In addition to the experimental methods and data presented, Multi-Continuum Theory (MCT) was used to predict and analyze the onset of damage and ultimate failure of a biaxially loaded IM7/977-2 laminate. The laminated architecture of advanced fiber-reinforced composite structures generates complex three-dimensional stress states even under simple uniaxial loading which is difficult to accurately represent numerically. As has been demonstrated repeatedly in the literature, conventional analysis techniques have difficulty accurately predicting these stress states. Most recently, the completion of the World-Wide Failure Exercise (WWFE) [1] exposed the lack of a single unified failure theory within the composite community that can accurately predict the initial onset and final failure of a general laminate under general loading. Almost all of the nineteen failure theories tested worked well in some and poorly in remainder of the fourteen test cases: four different fiber/matrix combinations, six different laminate stacking sequences and approximately six different (uniaxial and biaxial) loading conditions. While more advanced failure analysis techniques are continuously being developed, there are very few instances where both numerical and experimental techniques are developed in parallel in the under the same effort towards the same goal.

Structural damage of a composite material begins at the level of its constituents and may, in fact, be limited to only one constituent in some situations. Conventional analysis using blending methodology, e.g., blending fiber and matrix material properties to develop effective lamina (composite) properties, loses the ability to examine constituent level behavior where damage initiates. This makes it analytically difficult to accurately predict pre-, ongoing, and post-damage conditions of the laminate. Conversely, the ability to accurately predict constituent damage throughout a laminate allows for a high resolution failure analysis of any composite structure from the initiation of damage to ultimate rupture, promoting more efficient remedies to improve the design. MCT [9,10] incorporates the classical micromechanics based strain-decomposition technique of Hill [11] into a numerical algorithm that extracts the stress and strain fields for a composites' constituents. Thus, MCT retains the basic nature of the composite's constituents (fiber and matrix) in a structural analysis as separate but linked continua so that the responses of these most basic components can be determined at every point in the structure. MCT does this in an efficient manner that result in a high resolution window on the behavior of a composite structure at its most basic level, i.e., the individual constituents. Constituent stress- or strain-based failure criterion can then be used to construct a nonlinear progressive failure algorithm for investigating the material failure strengths of composite laminates.

2 Experimental Procedures

The experimental portion of the present study began by generating reliable uniaxial stiffness and strength results of a unidirectional IM7/977-2 carbon/epoxy laminate. The utility of these data were twofold. First, they represented a partial set of input parameters required for the numerical analyses of the current study. Secondly, the collective data set represented the data to estimate the uniaxial strength of the quasi-isotropic IM7/977-2 laminate to later be compared with unidirection results generated from the biaxial test specimen, as previously described. Due to space limitations of the current paper, only a brief description of the uniaxial test results will be provided; however, the interested reader is referred to the applicable references for additional information regarding the test procedures used [13-15]. All results presented in Table 1 and the rest of this document adopts the composites nomenclature of Hyer [16]. Reviewing the data of Table 1, a high degree of confidence is established as the data are very consistent, generally having a Coefficient of Variation around 5% for all tests and the fact that it compares well with other data sets [17]. It is worth emphasizing that the unidirectional properties presented in Table 1 are for unidirectional lamina only and do not represent the quasi-isotropic response of the same material. However, the data of Table 1 will be used as input properties to predict the quasi-isotropic response using MCT techniques, as described later.

Table 1. Uniaxial Material Properties for IM7/977-2 Carbon/Epoxy Unidirectional Laminate. Fiber Volume = 66.4%.

	Compression [13]		Tension [14]		Transverse Tension [14]		Shear [15]	
Specimen	Suc	Ec	Sut	Et	Sut	Et	τ_{12f}	G12
No	(Ksi)	(Msi)	(Ksi)	(Msi)	(Ksi)	(Msi)	(Ksi)	(Msi)
1	214	22.5	406	24.2	11.5	1.4	13.8	0.75
2	250	22.1	423	24.6	10.4	1.4	13.1	0.79
3	225	22.5	403	25.3	11.7	1.3	13.6	0.75
4	220	21.8	408	26.9	11.0	1.4	13.7	0.73
5	226	22.9	436	25.7	10.4	1.4	14.1	0.81
6	212	21.3	N/A	N/A	N/A	N/A	N/A	N/A
Average	**225**	**22.2**	**415**	**25.3**	**11.0**	**1.4**	**13.7**	**0.77**
COV (%)	6.1	2.6	3.4	4.1	5.5	1.7	2.7	4.1

The biaxial tests for the present study began by defining a successful configuration as one in which specimen failure, at maximum load, must occur in or around the specimen's gage section. Biaxial strengthening effects can make this a difficult objective to obtain for certain laminate architectures in general and a quasi-isotropic one in particular. Using biaxial cruciform specimens, Figure 2, it is therefore reasonable to expect unacceptable failures to occur in the arms (which are loaded uniaxially) rather than in the biaxially loaded, hence strengthened, gage section. In previous research [3-5] cross-ply laminates have been successfully tested, in part, to their low in-plane Poisson's response (offaxis terms in the stiffness matrix, which account for internally generated multiaxial stress states, are a function of Poisson's ratios). Furthermore, the experience gathered by the current authors led them to believe that a fiber reinforced quasi-isotropic laminate (which exhibit a larger in-plane Poisson's response) could be successfully tested provided appropriate specimen geometry and sufficient reinforcement was placed in the loading arms.

Although various cruciform configurations have been studied [4], the focus of this program was to fabricate and test a quasi-isotropic laminate. Existing failure theories indicate that a quasi-isotropic laminate would be significantly (2x) stronger when loaded biaxially than when loaded uniaxially. Experimentally this increases the probability of premature failure in the uniaxially loaded arms resulting in an invalid test. To prevent this, a quasi-isotropic laminate was designed with integrated cross-ply tabs on the arms using a $[(0/90)_4(0/45/\text{-}45/90)_2]_S$ laminate configuration. The thickness-tapered cruciform specimens were initially laid-up as flat laminate plates from which the desired cruciform specimen shape, including gage section, was machined out using a computer numeric controlled (CNC) mill and high-speed router. That is, in physically machining the specimen to the desired thickness, the (0/90) portions of the laminate was removed from the gage section but retained in the loading arms. Material remaining in the gage section was the desired (0/45/-45/90) quasi-isotropic laminate to be tested. A total of sixty-six thickness-cruciform specimens were fabricated for testing in twelve different biaxial stress ratios, three repetitions each, to determine the strengths in each of the four quadrants in $\sigma_1 - \sigma_2$ stress space. Approximately 1/3 of the test specimens were instrumented with either uniaxial or biaxial strain gages to monitor the strain to failure.

The biaxial tests were performed utilizing the triaxial testing facility shown in Figure 1. This electromechanical test facility was developed specifically to evaluate the biaxial (two-dimensional, in-plane) and triaxial (three-dimensional) response of composite materials. This experimental test facility is capable of generating any combination of tensile or compressive stresses in $\sigma_1 - \sigma_2 - \sigma_3$ stress space [3,4,8].

Because cruciform-shaped specimens have two intersecting loading directions, there exists the possibility of load transfer between adjacent loading arms. That is, a portion of the load applied by one arm in one direction may be reacted by another loading arm bypassing the gage section and leading to inaccurate assumptions of biaxial stress levels in the gage section. Fortunately, it is possible, but not trivial, to quantify the levels of load sharing for each material system and specimen geometry. Referred to as the *bypass correction factor (BCF)*, this value gives an indication of the amount of applied force that bypasses the thickness-tapered gage section [3,4].

Since this study represented one of the first effort involving quasi-isotropic laminates, considerable effort was expended to determine the exact value of the bypass ratio for each specimen tested. The process began by mounting a single uniaxial strain gage placed in the center of the gage section. Using this gage, the actual stress level in the gage section of a thickness-tapered cruciform specimen was obtained by multiplying the measured strain by the effective modulus of elasticity of the laminate (developed via Classical Lamination Theory [16]) being tested. To minimize extraneous variables during this procedure, the cruciform specimen was loaded uniaxial, i.e., only one pair of opposing arms was loaded. The stress results generated using this configuration were then simultaneously compared to stress values obtained by dividing the applied force (average value of both opposing load cells) measured along a loading axis by the cross-sectional area of the thickness-tapered cruciform specimen gage section. A comparison of these two stress values quantifies the *BCF* as the amount of load that is bypassing the gage section of the cruciform specimen. That is, the bypass correction factor is determined by:

$$BCF = \frac{(Modulus)_{effective}(\varepsilon)_{measured}}{(Load)_{measured}/(Area)_{measured}}$$

Any geometric modifications to the thickness-tapered cruciform specimen will require a new *BCF*. The motivation behind quantifying the *BCF* in terms of stress levels is that to eliminate the need for strain instrumentation on every specimen. The specific *BCF*s used for the present study were 0.86 and 0.79-0.87 for tensile and compressive loadings, respectively.

Once each thickness-tapered cruciform specimen was machined, the procedure for generating ultimate biaxial strength values began by loading each cruciform specimen into the triaxial testing facility shown in Figure 1 in accordance with established practices [3,4]. Each specimen was loaded at a rate of 1.27 mm/min while maintaining the appropriate stress ratio until ultimate specimen failure occurred. The stress ratio was performed in load control by maintaining a constant ratio of applied stress in the global x-direction (drive axis) to the applied stress in the global y-direction (slave axis). The notation,

$$\text{stress ratio} = (Load)_x / (Load)_y \,,$$

is used to identify a particular stress ratio, with a positive sign indicating tensile and a negative sign indicating compressive values. For example, a stress ratio of 1/-2 denotes a test in which the magnitude of the compressive stress applied in the y-direction is twice that of the tensile stress applied in the x-direction. The stress ratios performed in the present study for the quasi-isotropic laminate were 1/1, 3/2, 2/1, 3/1, 1/0, 2/-1, 3/-1, 1/-1, 1/-2, -1/0, -1/-2, -1/-3 and -1/-1. Finally, the measured biaxial strength of each specimen was corrected using the associated *BCF*. A *BCF* has been applied to all experimental data presented in this paper. Figure 3 represents a photograph of a biaxial test specimen loaded in a -1/-1 stress ratio until ultimate failure. The symmetric failure through the gage section leads the authors to have a considerable amount of confidence that the current experimental test methods are generating accurate failure data, as any other failure surface would indicate sub-optimal test conditions and results.

Fig. 3. Thickness-Tapered Cruciform Specimen Failure Surface when Subjected to -1/-1 Loading Conditions.

3 Numerical Procedures

Multi-Continuum Theory [9,10] (MCT) was used to analytically predicted the IM7-977 $[0/90/\pm45]_S$ failure envelope. MCT incorporates the classical micromechanics based strain-decomposition technique of Hill [18] into a numerical algorithm that extracts the stress and strain fields for a composite's constituents. Thus, MCT retains the basic nature of the composite's constituents (fiber and matrix) in a structural analysis as separate but linked continua so that the responses of these most basic components can be determined at every point in the structure.

To capitalize on the information, MCT uses a constituent-based, quadratic, stress-interactive, failure criterion originally proposed by Hashin [19] but modified by Mayes [20]. MCT has been incorporated into a proprietary finite element code [12,2] as well as user-defined subroutines in commercial codes such as ANSYS™ and ABAQUS™.

The fiber failure criterion is,

$$K_{1f} I_{1f}^2 + K_{4f} I_{4f} = 1$$

where

Ii are the transversely isotropic stress invariants;

$$I_1 = \sigma_{11},$$

$$I_2 = \sigma_{22} + \sigma_{33},$$

$$I_3 = \sigma_{22}^2 + \sigma_{33}^2 + 2\sigma_{23}^2,$$

$$I_4 = \sigma_{12}^2 + \sigma_{13}^2,$$

$$I_5 = \sigma_{22}\sigma_{12}^2 + \sigma_{33}\sigma_{13}^2 + 2\sigma_{12}\sigma_{13}\sigma_{23},$$

$$^{\pm}K_{1f} = \frac{1}{^{\pm}S_{11f}^2},$$

$$K_{4f} = \frac{1}{S_{12f}^2},$$

$^{\pm}S_{11f}$ denotes fiber normal strength. The ± symbol indicates that the appropriate tensile or compressive is used depending on the constituent's stress state.

S_{12f} denotes fiber shear strength.

The matrix failure criterion is,

$$^{\pm}K_{3m} I_{3m} + K_{4m} I_{4m} = 1,$$

where

$$^{\pm}K_{3m} = \frac{1}{^{\pm}S_{22m}^2 + {}^{\pm 22}S_{33m}^2},$$

$$K_{4m} = \frac{1}{S_{12m}^2}.$$

The mode of composite damage, fiber or matrix initiated, is determined by monitoring the constituents respective failure criteria. The relative contribution of the various stress components to initial, intermediate, and final constituent failure states can be determined by examining the product of the failure parameter $K_{i\beta}$ and its associated stress invariant $I_{i\beta}$.

Two finite element models were used to develop the failure envelopes. The first was a geometrically representative model of the cruciform test specimen. Figure 4 is the resulting cruciform FE model after utilizing three planes of specimen symmetry (modeling 1/8th of the original configuration) and eliminating some unnecessary loading arm length. The model contained 816 eight node tri-linear solid elements, eight layers within each element, 1242 total nodes and 3726 system degrees of freedom. Figure 4 is verification that a symmetric load (+1/+1) produces a symmetric stress distribution and uniform stress within the gage area. The second model was a single finite element, with appropriate boundary conditions, which simulated the far-field three-dimensional stress state at the geometric center of the specimen.

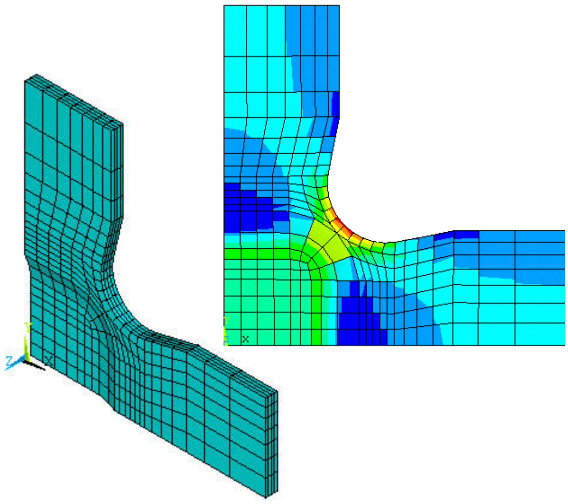

Fig. 4. One-Eighth Symmetry Cruciform Finite Element Model.

MCT's ability to calculate accurate constituent stress and strain fields is dependent on constituent elastic constants derived from experimentally determined composite values. Further, MCT's ability to execute realistic failure analysis is dependent on accurate values for constituent strengths, also derived from experimentally determined composite values. The link establishing a relationship between composite (macro) and constituent (micro) elastic constants is a finite element micromechanics model for a continuous fiber unidirectional composite. The finite element micromechanics model used in this research was advanced by Garnich [21]. The results of the micromechanics properties developed for an IM7-977-2 lamina with 0.63 fiber volume fraction is presented in Tables 2 and 3.

Table 2. Micro-Macro Consistent Elastic Constants.

Material	E_{11} (Msi)	E_{22} (Msi)	G_{12} (Msi)	G_{23} (Msi)	ν_{12}	ν_{23}	α_{11} (10^{-6}/°C)	α_{22} (10^{-6}/°C)
IM7-977 lamina	25.3	1.18	0.768	0.417	0.272	0.415	2.47	27.5
IM7 fiber	40.0	2.00	13.8	0.801	0.220	0.250	-0.40	5.60
977 matrix	0.500	0.500	0.182	0.182	0.370	0.370	50.4	50.4

Table 3. Micro-Macro Consistent Strengths.

Material	${}^{+}S_{11}$ (ksi)	${}^{-}S_{11}$ (ksi)	${}^{+}S_{22}$ (ksi)	${}^{-}S_{22}$ (ksi)	S_{12} (ksi)	S_{23} (ksi)	${}^{+22}S_{33}$ (ksi)	${}^{-22}S_{33}$ (ksi)
IM7-977 lamina	415.	-225.	11.0	-22.9	14.8	-	-	-
IM7 fiber	637.	-345.	-	-	18.3	-	-	-
977 matrix	-	-	11.3	-23.6	7.30	-	-1.71	-6.06

4 Results and Discussion

Figure 5 presents experimentally and analytically generated biaxial failure envelopes for the quasi-isotropic IM7/977-2 laminates tested. Both the experimental and analytical data assume symmetry of the load and laminate which creates a line of symmetry in the figure +45° to the abscissa with a zero ordinate intercept. Only one half of the data points shown in Figure 5 were actually determined (lower half of quadrants I and III, all of quadrant IV) with the remaining points being a mirror reflection across the line of symmetry.

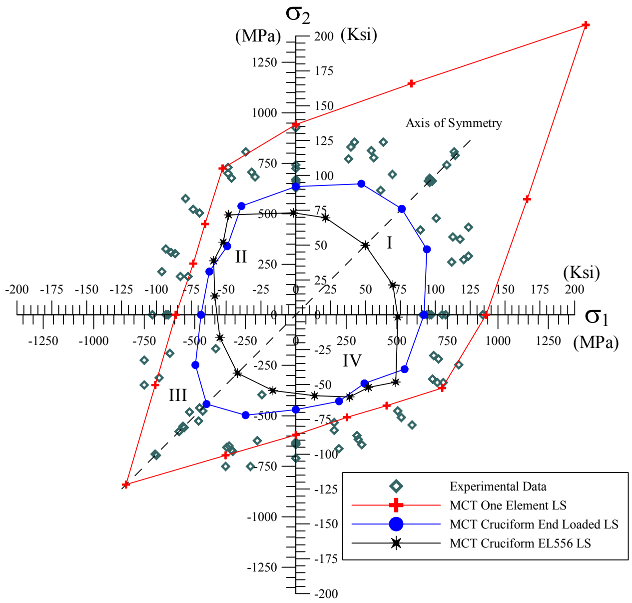

Fig. 5. Experimental and Analytical Biaxial Failure Envelopes for an IM7/977-2 Quasi-Isotropic Laminate.

Three analytical prediction envelopes (9 data points per envelope) are shown: 1) That from the one element model representing the far field stress at the geometric center of the test specimen, 2) The traction applied at the load arm ends of the cruciform model and 3) The stress state of a single element (# 556) located adjacent to the three planes of symmetry in the cruciform model. Each model has its own virtue. The one element model is easy to construct and very fast to analyze. The traction represents the average stress of all the elements in the cruciform model The stress state of element 556 is representative of (and numerically almost identical to) the volume average stress of all the elements located within the gage section.

The correlation between the one element failure envelop and experimental data is reasonably good in quadrants II, III and IV but drastically exceeds the experimental data in quadrant I. The cause of non-correlation is not clear at this time. The traction envelop conservatively correlates with the experimental data in all quadrants. It most notably misses correlating on the uniaxially loaded compressive axes but paradoxically correlates well on the uniaxially loaded tensile axes. Again, the cause of non-correlation in this region is not clear at this time. The gage section volume average stress severely under predicts the experimentally determined failure in all quadrants. A closer look into the causes of this poor correlation is required.

In the finite element method, numerical methods sample stress, strain, and material values at Gauss quadrature points. MCT failure analyses store a state variable corresponding to composite material damage at each of these Gauss points. Three composite material conditions or states, listed in increasing damage severity, are defined as: 1) undamaged composite, 2) composite damaged by matrix failure, and 3) composite damaged by fiber failure. When either constituent fails, all its moduli are immediately reduced to a near zero value at that Gauss point. Since all constituent properties, both intact and failed, are known a priori, the micromechanics model is used to determine two additional sets of composite properties, corresponding to damage states 2 and 3 before conducting a MCT failure analysis.

As shown in Figure 6 (+1/+1 load case), damage in the cruciform model generally began as matrix failure in the fillet that transitions the thicker loading arm into a gage region, proliferated to the radius section between the loading arms and ultimately progressed into catastrophic failure of the fiber constituent.

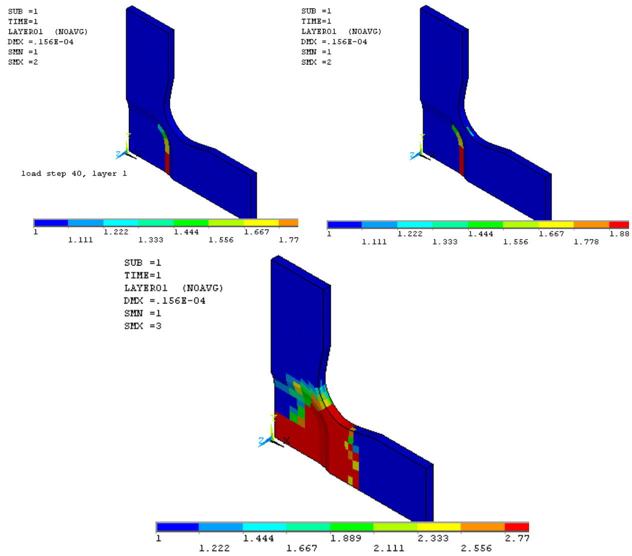

Fig. 6. Progressive Composite Damage for 1/1 Load Condition.

Table 4 lists the damage initiation locations, modes and load history for each case. In eight out of the nine cases composite damage began as matrix failure in the fillet. Interestingly, the matrix failure occurred in a 0º lamina and not a ±45º as one might expect. In the ninth case, -1:-1, structural rupture occurred in a single step with compressive fiber failure. A closer look at the fillet, Figure 7, reveals there are essentially only two elements making the transition from load arm to reduced thickness gage section. The fillet, by its very definition, is used in areas of high strain/stress gradients. The general rule in finite elements is to use dense element meshes in areas of high gradients. Further, it is the author's experience that progressive damage analyses are very sensitive to mesh density as low density meshes do not provide the alternate load paths necessary to maintain equilibrium once a localized region is damaged. Thus the possibility that the analytical results could be significantly improved by increasing mesh density it almost assured.

Table 4. Damage Initiation Location and Constituent Failure.

Load Ratio	Element/ layer	1st /Last Failure Load Step	Primary Term	Secondary Term	Failure Mode
+1:+1	293/0º	30/38	$K_{4m}I_{4m}$=0.734	$K_{3m}I_{3m}$=0.275	Matrix-shear
+1:+½	293/0º	30/47	$K_{4m}I_{4n}$=0.947	$K_{3m}I_{3m}$=0.113	Matrix-shear
+1:0	293/0º	28/46	$K_{4m}I_{4m}$=0.960	$K_{1f}I_{1f}$=0.062	Matrix-shear
+1:-½	293/0º	23/39	$K_{4m}I_{4m}$=0.930	$K_{3m}I_{3m}$=0.075	Matrix-shear
+1:-1	293/0º	21/25	$K_{4m}I_{4m}$=0.991	$K_{3m}I_{3m}$=0.033	Matrix-shear
+½:-1	300/90º	27/31	$K_{4m}I_{4m}$=0.933	$K_{3m}I_{3m}$=0.073	Matrix-shear
0:-1	300/90º	32/34	$K_{4m}I_{4m}$=1.030	$K_{3m}I_{3m}$=0.010	Matrix-shear
-½:-1	300/90º	35/36	$K_{4m}I_{4m}$=0.974	$K_{3m}I_{3m}$=0.028	Matrix-shear
-1:-1	345/-45	32/32	$K_{1f}I_{1f}$=0.998	$K_{4f}I_{4f}$=0.009	Fiber-compress

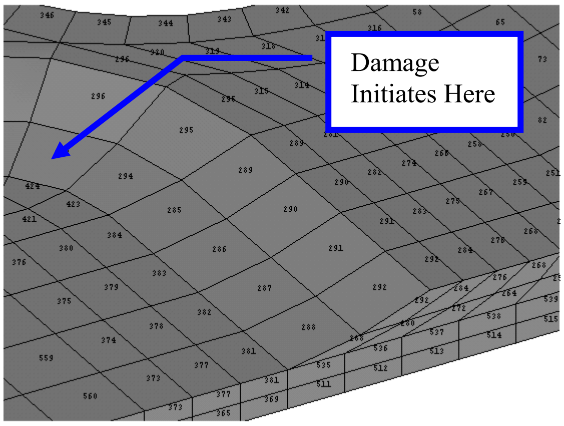

Fig. 7. Magnified View of the Fillet Transition to the Gage Section.

A laminate of $[0/90/\pm45]_S$ architecture is called "quasi-isotropic" because the in-plane symmetry of the elastic constants and strengths. A natural extension to a failure analysis of this laminate is to compare it to well accepted failure criteria for ductile isotropic metals. Two widely popular criteria are the Maximum Shear Stress, also known as the Tresca criterion, and the Distortional Strain Energy Density; also know as the von Mises criterion [22] (Figure 8).

In view of these isotropic criteria there appears to be a degradation of laminate strength in the shear regions (quadrants II and IV) indicating a high degree of stress-interaction. Conversely, no stress interaction appears in Quadrants I and II of the experimental data and the maximum shear failure analysis.

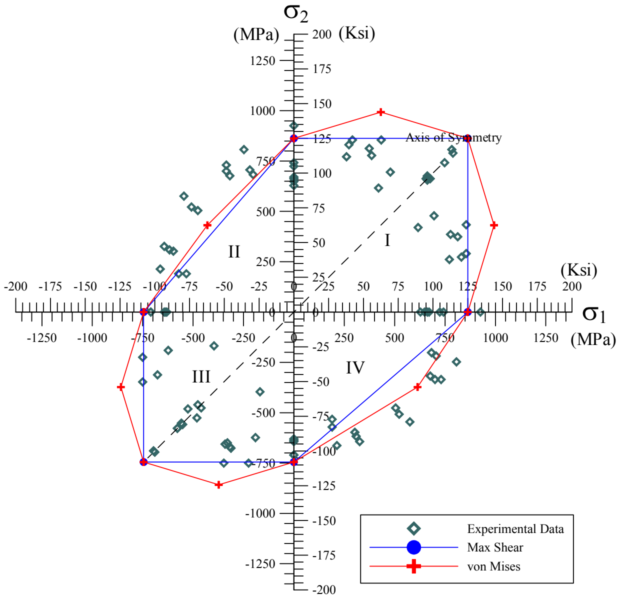

Fig. 8. Isotropic Failure Envelopes for IM7-977-2 Quasi-Isotropic Laminate.

Further, it is interesting to compare the IM7-977 results to those generated using an AS4-3501 composite material. The MCT AS4-3501 material properties are a solid, well tested data set in which we have high confidence. As mentioned previously, constituent strengths are derived from experimentally determined lamina strengths. Determining which constituent precipitates composite failure is necessary for establishing accurate constituent failure values. Identifying the constituent that precipitates failure in longitudinal and transverse lamina tension and compression tests is intuitive and straightforward, i.e., fiber failure for longitudinal loads and matrix failure for transverse loads. Identifying the constituent leading to shear failure is more problematic, as non-catastrophic matrix and fiber damage begins well before ultimate composite strength is achieved [23].

In an effort to more rigorously determine the constituent shear strengths, a procedure using nonlinear regression analysis of load cases involving shear has been developed previously [23]. Data from off-angle, balanced, symmetric laminates, $[\pm\theta]_S$, provided an excellent basis for determining optimized constituent failure parameters. These laminates produced varying degrees of combined shear and normal stresses and tended to fail in modes that allowed analytical identification of the constituent precipitating laminate failure. The AS4-3501 MCT material data set has undergone this development the IM7-977 has not.

5 Conclusions

The author have presented an analytical and experimental analysis of biaxial loading of a IM7 carbon fiber/977-2 epoxy matrix, quasi-isotropic, $[(0_N/90_N/\pm45_N)_M]_S$ composite laminate. The numerical predictions were generated using classic strain decomposition technique known as Multicontinuum Theory and an associated constituent based, stress-interactive, quadratic failure critera. The experimental results were generated using thickness-tapered cruciform specimens on a triaxial material test facility located at the Air Force Research Laboratory at Kirkland Air Force Base. A geometrically representative finite element model as well as a single element model was employed using MCT to generate multiple numerical predictions for this particular laminate configuration. Correlation between experimentally and analytically generated results varied depending on the specific numerical model used, exposing the paramount requirement for accurate input material properties when using advanced composite analysis techniques, as well as the general difficulties encountered when predicting the failure of composite materials. The authors provide discussion regarding several possible explanations for the discrepancy between experimental data and numerical models and offer insight into material behavior and accurate predictive techniques that could be pursued. The authors presented several aspects of the current procedures that should be reconsidered in future efforts to generate more accurate results.

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