**Data-driven Prognostics for Fiber Reinforced Composites**

**Based on Multimodal NDE Monitoring**

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**Keywords:** Damage, Composites, Acoustic Emission, Digital Image Correlation, Infrared Thermography

**Abstract**

Multimodal Nondestructive Evaluation (NDE) is used in this investigation to estimate the evolving material state in carbon fiber reinforced composite specimens to subjected mechanical loading. Specifically, Acoustic Emission (AE) monitoring, Digital Image Correlation (DIC) measurements and passive Infrared Thermography (pIRT) are used to monitor damage in IM7-8552 specimens. Both pristine Straight Edge (SE) and Open Hole (OH) specimens were loaded until failure to monitor the damage evolution and link this to the observed NDE trends. Post mortem microscopy coupled with in situ NDE identified that while multiple damage mechanisms were present, delamination is the dominate mode of catastrophic failure. The in situ monitored NDE data trends are leveraged in a machine learning framework combining unsupervised clustering and outlier analysis to denoise the recorded data and produce a degradation curve that can be used in a diagnostics and prognostics FEA approach. A computational framework capable of performing 3D FEA analysis and providing predictions of the distributed damage within the composite layers using real-time recorded damage data trends is presented and the use of this methodology is discussed in terms of its material and loading agnostic nature and in particular its applicability and potential in forming data-driven prognostics of remaining useful life.

1. Introduction

Early and reliable identification of damage is crucial to the determination of component safety, prediction of remaining useful life, as well as design of materials for demanding engineering applications. Damage is a multiscale process especially when incubation and initiation are concerned. Abundant information found in the pertinent literature shows a large dependence of damage on the actual microstructure for a variety of materials including Iron [1], aluminum [2-4], magnesium [5-7], and titanium [8] where microstructure effects have been shown to play a large role in material properties, most notably in fatigue life investigations.

In the case of carbon fiber reinforced composites, there is a strong dependency of the dominant failure modes on the stacking sequence and thickness of the individual plies [9]. For example, by increasing the ply thickness from 0.125mm to 0.25mm for the case of [45/-45/90/0]s and [90/45/0/-45]s a correlation between failure mode and strength was observed. Unnotched specimens with different ply block thicknesses and numbers of sub-laminates showed differences in strength of nearly a factor of three, with failure initiating by delamination at the free edge. The open-hole tension specimens also failed by delamination for thick ply blocks, especially when the ratio of ply thickness to ligament width was large. Specimens with dispersed thin plies failed by fiber fracture before reaching the necessary stress to delaminate across the width [10].

The microstructural response to various loading schemes has been used to inform models used for fatigue life prediction [2, 3, 11-13]. In addition, several nondestructive evaluation techniques (NDE) have been used to perform similar predictions at the component or structural level [14-26]. To achieve this goal, real time recorded NDE information is correlated typically with macroscopically measured mechanical data and is paired with post mortem microscopic examination [6, 27-29]. Therefore, a critical gap can be identified in both the quantification and validation of NDE information obtained at the meso- and macroscales that contains information on damage from the microscale. To this effect scale independent NDE techniques such as DIC and AE can be used to monitor the evolution of a material or structure to perform diagnostics and obtain state information that can be fed to a model for prognostics and remaining useful life (RUL) predictions. Furthemore, during fatigue loading, especially for composites, passive Infrared Thermography (pIRT) has been reported as a method to monitor temperature changes due to external loads [30]. In pIRT localized changes of temperature can be used as a method to monitor damage growth [31]. In this context, Reifsnider and Williams [32] showed the correlation between the generation of heat and fatigue damage development in boron–aluminium and boron–epoxy composites.

Damage models discussed in the literature generally focus on defining the material degradation due to damage using a set of equations that target the particular role of individual mechanisms. In several cases, a damage variable, D, is defined as the ratio between the damaged and the total area of a reference volume. If damage is isotropic a scalar damage variable is then defined; anisotropic damage leads to the adoption of a second order damage tensor. The damage parameter has a value of zero in the undamaged state and a value of one when final material failure has occurred [33]. In this context, Hatzigeorgiou et al. [34] presented a damage model for concrete in which a singular damage parameter is used to account for asymmetric tension and compression behavior. Other efforts in this field include the work by Kuna and Wippler [35], who used a unified Chaboche model derived from a free energy potential which was enhanced to account for void growth. A thermodynamic approach was used in Richard et al. [36] to model damage in quasi-brittle materials. Other efforts have brought a more physics-based approach to the definition of damage. For example, Liu and Zheng [37] provided a review of damage modeling techniques in composite laminates including the use of phenomenological damage tensors in continuum damage models and multiscale finite element methods that derive their damage parameters via stochastic analysis of the underlying micro-mechanisms. Moreover, Rinaldi et al. [38] introduced a microstructure-aware damage parameter in two-dimensional lattice models that is related to the coherence length between microcracks. Other microstructure-sensitive computational modeling methods for fatigue crack formation are reviewed in McDowell and Dunne [39].

Finite element analysis has been mostly utilized to predict not only the onset of failure but also the progressive failure up and the damage path in composite materials [1]. For this purpose, various failure theories can be employed including the maximum stress, maximum strain, Hashin, Tsai-Hill, and Tsai-Wu failure theories. In general, there are two different approaches to study the damage process: continuum damage mechanics and fracture mechanics. The former describes the damage evolution using the constitutive relations and stiffness degradation, while the latter uses methods such as the virtual crack closure technique (VCCT), extended finite elements (XFEM), and the cohesive zone model (CZM) to model cracks on the scale of the structure. More specifically, Bogert et al. [2] investigated intra-laminar damage in center notched composites by implementing the progressive failure methodology in both explicit and implicit finite element codes. They concluded that since no global inversion is performed in explicit code, this procedure does not lead to the matrix singularities and as a result it can be used for complex loading and nonlinear dynamic interactions of damage and structure. Often, the finite element method requires remeshing to predict damage evolution accurately. Moreover, the assumption of lamina homogeneity is questionable and can affect the accuracy of the failure prediction. To overcome this difficulty, Kilic et al. [3] employed an explicit peridynamic model of fibers and matrix material for progressive damage prediction in composite laminates. They considered distinct properties of fiber and matrix and their fractions.

This article presents a data-driven prognostics model for composite specimens by coupling computational modeling with nondestructive evaluation techniques to obtain real time state awareness of the material. Particularly Acoustic Emission (AE) information obtained from standardized ASTM-sized IM7/8552 specimens is related to and cross validated with data obtained from Digital Image Correlation (DIC) and IR thermograpy to identify the material’s state using an outlier analysis approach. The results are then used as an input into a Finite Element (FEA) based frame work to perform behavior simulations and RUL predictions. In this work, a commercial simulation software called GENOA (General Optimization Analyzer) was used [40, 41]. GENOA uses multi-scale progressive failure analysis (MS-PFA) considering the effects of defects, geometry, material properties and manufacturing. The failure at the ply level is assessed based on the ply strength/strain limits. The degraded stiffness of the damaged plies is calculated based on micro-crack density. The results presented demonstrate that multimodal NDE combined with post-processing toolds can provide inputs to computational modeling which can then be used in a data-driven framework to provide predictions of the damage state and remaining useful life in composites.

2. Techniocal Approach

## 2.1. Material and Testing Setup

The material used is carbon fiber – epoxy unidirectional (UD) prepreg system, IM7/8552, manufactured by Hexcel. The UD prepreg tapes have a nominal ply thickness of 0.315mm. The laminates were cured according to the Hexcel’s recommendations for cure cycles. The composite specimens manufactured with 16 layers and a layup of [45/0/-45/90]2S using unidirectional prepreg layup technics with a nominal ply thickness of 0.315mm was obtained and used for this work. Straight edge (SE) samples, shown in a Fig 1a were designed using ASTM D3039 and are used to examine the behavior and damage evolution of the material in the pristine condition, while open hole (OH) samples, shown in a Fig 1b were designed using ASTM D5766 as a “predamaged” condition. All specimens had a final thickness of 5 mm and width of 25mm. The SE and OH specimens were loaded with a displacement rate of 2 mm/min until catastrophic failure defined as a load drop of 60% of the ultimate load using an MTS 370.10 Landmark Servo-hydraulic Test machine with hydraulic grips.



**Figure 1** Specimen Geometry for (a) straight edge sample and (b) open hole sample

The material response was monitored using three nondestructive evaluation (NDE) methods combining surface and volume observations via Acoustic Emission (AE), Digital Image Correlation (DIC) and passive Infrared Thermography (pIRT). AE was monitored using 4 PICO sensors (150 to 750 kHz operating frequency) mounted at the locations indicated by a red *x* in Fig. 1. A Peak Definition (PDT), Hit Definition (HDT), and Hit Lockout Time (HLT) of 100, 500, and 500 μs respectively as used to record all waveforms. All AE waveforms were recorded at 10 million samples per second (MSPS) to avoid aliasing of the recorded waveform using a PCI-2 data acquisition board with an analog filter between 100 and 1000 kHz which represents the closest filter available to the AE sensor range. All waveforms were further filtered in post processing to the operating range of the sensor using a 10th order digital butterworth bandpass filter. The surface of the specimen was monitored with DIC to observe the localization and evolution of the strain concentrations that occur as a result of the mechanical load. DIC monitoring was achieved using a stereo system to monitor both in plane strain components and out of plane motion with a frame rate of 1 Hz. The speckle pattern was applied using commercially available spray paint with black dots applied to a base white layer resulting in a subset and step size of 25 and 10 pixels (1.35 and 0.54 mm) respectively and a maximum noise level of 1100 μm/m. Additionally, average strain is calculated using a virtual extensometer placed across the entire gage length of the specimen to provide reliable global strain measurements throughout the entire test. Further, pIRT is used to monitor the thermal energy release that results from damage. Furthermeore, a FLIR A325sc camera with a 320 x 240 resolution and a detectible temperature range between 0 and 350°C was used. Video was recorded at 14 Hz and images were post processed to observe the change in temperature between frames rather than monitor the absolute temperature.

## 2.2. Computational Modeling

GENOA which is a commercially available failure analysis software (produced by AlphaSTAR) is implemented in this investigation to simulate tensile tests similar to the experiments reported. To obtaine values for the mechanical properties used in GENOA, five ASTM-defined simulated tests, including tension and compression in the transverse and longitudinal directions as well as shear, were performed on models of unidirectional single ply laminas. The obtained values are given in Table 1 and Table 2, respectively.

**Table 1** Reverse engineered effective matrix properties

|  |  |  |  |
| --- | --- | --- | --- |
| Matrix Material Properties | Symbol | Effective | Units |
| Young's Modulus | Em | 4.67 | [Gpa] |
| Poisson's Ratio | vm | 0.42 | [-] |
| Tension Strength | SmT | 97.3 | [Mpa] |
| Compression Strength | SmC | 433.9 | [Mpa] |
| Shear Strength | SmS | 185.9 | [Mpa] |

**Table 2** Reverse engineered effective fiber properties

|  |  |  |  |
| --- | --- | --- | --- |
| Fiber Material Properties | Symbol | Effective | Units |
| Longitudinal Young's Modulus | Ef11 | 206.84 | [Gpa] |
| Transverse Young's Modulus | Ef22 | 14.67 | [Gpa] |
| Poisson's Ratio | vf12 | 0.24 | [-] |
| Poisson's Ratio | vf23 | 0.39 | [-] |
| Shear Modulus | Gf12 | 11030 | [Mpa] |
| Shear Modulus | Gf23 | 5278 | [Mpa] |
| Longitudinal Tension Strength | Sf11T | 3684 | [Mpa] |
| Longitudinal Compression Strength | Sf11C | 1826 | [Mpa] |

Furthermore, a micro mechanics model and specifically the equivalent constraint model (ECM), was embeded in the progressive failure finite element analysis of GENOA to investigate the initiation and evolution of microcracks. Three parts are included to predict the crack density: 1) the emergence of cracks, 2) the multiplication of cracks, and 3) the degradation of composite properties due to the existence of cracks at each location. The micro-crack spacing was assumed uniform. In addition, only transverse cracking was considered in the micro mechanics model [44].

This information was then used in the model shown in Fig 2. Shell elements were used with a mesh refinement near the edges to account for potential edge effects expected based on experimental results. The red boxes indicate the areas where boundary conditions were applied similar to the area where tabs are used in the experiments. In this case the left end of the specimen was held fixed while the right hand side was subjected to a 0.01 mm displacement to mimic the experiments discussed previously. The simulation ends at 1.17% applied strain as in accordance with the experiments shown.



**Figure 2** FEA model

In addition, maximum stress and strain based criteria were chosen for this analysis which are given in Table 3. In the case of 90 degree plies, the Modified Distortional Energy (MDE) criterion was disabled. For 90 degree plies if MDE gets triggered than it overtake transverse tensile criteria and results in sudden degradation rather than gradual degradation as expected based on experimental results in the 90 degree ply. A detailed description of these criteria is given in the Appendix.

**Table 3** Damage (lamina) and fracture (laminate) criteria

|  |  |  |
| --- | --- | --- |
| **Failure Criterai Name** | **Damage** | **Failure** |
| **Maximum Stress Based Failure Criteria** |  |  |
| **Fiber Failure Criteria** |  |  |
| (S11T) Longitudinal Tensile | Enable |  |
| (S11C) Longitudinal Compressive | Enable | Enable |
| (F11C) Fiber Micro-Buckling | Enable | Enable |
| (R11C) Fiber Crush | Enable |  |
| (D11C) Delaminations | Enable | Enable |
| **Matrix Failure Criteria** |  |  |
| (S22T) Transverse Tensile | Enable |  |
| (S22C) Transverse Compressive | Enable |  |
| (S33C) Normal Compressive | Enable |  |
| (S12S) In-Plane Shear | Enable |  |
| **Delamination Failure Criteria** |  |  |
| (S33T) Normal Tensile | Enable |  |
| (S23S) Transverse Normal Shear | Enable |  |
| (S13S) Longitudinal Normal Shear | Enable |  |
| (RROT) Relative Rotation | Enable |  |
| **Maximum Strain Based Failure Criteria** |  |  |
| **Fiber Failure Criteria** |  |  |
| (EPS11T) Longitudinal Tension Strain | Enable | Enable |
| (EPS11C) Longitudinal Compression Strain | Enable | Enable |
| **Matrix Failure Criteria** |  |  |
| (EPS22T) Transverse Tension Strain | Enable |  |
| (EPS22C) Transverse Compression Strain | Enable | Enable |
| **Delamination Failure Criteria** |  |  |
| (EPS33T) Normal Tension Strain |  |  |
| (EPS33C) Normal Compression Strain | Enable | Enable |
| (EPS12S) In-plane Shear Strain | Enable | Enable |
| (EPS13S) Long. Out-of-plane Shear Strain | Enable | Enable |
| (EPS23S) Trans. Out-of-plane Shear Strain |  |  |
| **Interactive Failure Criteria** |  |  |
| (MDE) Modified Distortion Energy | Enable |  |
| (TSAI) Tsai Wu |  |  |
| (HILL) Tsai Hill |  |  |
| (HOFF) Hoffman |  |  |
| (HASH) Hashin |  |  |
| (PUCK) PUCK |  |  |
| (SIFT) Strain Invariant Failure Theory | Enable | Enable |

**3. Results**

**3.1 Mechanical and NDE**

The specimens behaved in an almost linear manner as seen in the stress train curves in a Fig 3. During loading, the entire specimen is uniformly loaded until a point were strain localizations appear. This is observed by the maximum strain as a function of imposed average strain plotted as the red curve in Fig 3. The point were the maximum strain deviates from the average strain corresponds to point 1 where a 45 degree strain concentration is observed which aligns with the fiber orientation of the observed ply. After this point, further concentrations appear and intensify as observed by the full field map at point 2 as well as the increase difference between the average and maximum strain values. After final failure strain concentrations are still observed that align with the fiber orientation in the material and a number of cracks are observed in this orientation.



**Figure 3** Stress-strain curve overlaid with the maximum strain value along with full field strain evolution revealing localizations in the ply orientation.

In addition to the accumulation of strain localizations, pIRT reveals the release of thermal energy at the time of damage by examining the difference in temperature from frame to frame. Figure 4 shows almost no change in the temperature of the material during the loading prior to final failure as either maximum or average temperature, however, the standard deviation has a continual decrease in value as the specimen is loaded and all thermal measure have a large sudden increase right at the time of failure. Further, the appearance of local “hotspots” that aligned with the 45 degree fibers in the top ply in the case of Fig 4a and 4b were observed. These “hotspots” are transient and disappear as quickly as they appear and mark the appearance of damage precursors. These precursurs are first observed at the point where the material deviates from a linear behavior at the location indicated by (a). Just prior to the final fracture of the specimen, a “hotspot” can be observed near the top of the specimen that does not align with the fiber orientation and is immediately followed by final fracture which releases thermal energy 10x greater than from the damage precursors observed leading to it.



**Figure 4**  Thermal Energy Evolution with full field themal maps for (a) 44 kN, (b) 51kN, (c) 66 kN, and (d) ultimate load of 67 kN

Overlaying the AE trends with the observed stress-strain of the specimen allows for the identification of damage precursor trends. Figure 5a shows the AE peak frequency as a function of the applied strain. AE activity with Peak frequencies between 0 and 100 kHz, appear almost immediately with content between 100 and 200 kHz appearing shortly after while the highest frequency signals between 700 and 800 kHz do not appear until 0.6% strain which occurs over halfway through the loading scheme. Looking at the evolution of AE hits and absolute energy as a function of strain reveals that the number of hits increase significantly at only 0.2% strain, while energy does not accumulate much until 0.6% strain. These observations indicate changes in the material response that may be the result of damage mechanisms activating and therefore can be considered damage precursors.



**Figure 5**  Acoustic emission data trends observed during mechanical loading of IM7-8552

Similar NDE data was obtained for the OH samples revealing the activation of the damage precurors earlier with respect to the results shows in Fig. 5b.

The damage precursor trends observed using AE, DIC and pIRT were then used to generate a damage evolution curve based on Mahalanobis Square Distance (MSD) which is a type of outlier analysis. Such damage curves were first generated for the SE and OH specimens using only the AE data. To accomplish this goal, every AE hit was compared to a baseline value that represents all noise sources such as the hydraulics and gripping noise by recording AE activity on a pristine sample under a small preload. Higher MSD values indicate further deviation from this baseline undamaged value and therefore represent more damage than lower values. The MSD value for each waveform was used to generate a cumulative MSD curve which was then normalized to have values in a range between 0, representing a pristine sample, and 1, representing catastrophic failure. Fig 6 shows the cumulative MSD for two SE samples calculated using only AE data. Both follow a similar trend with the damage value increasing near 0.2% strain and remaining almost linear until near the end of life where the slope increases. By contrast, the damage value calculated for the OH samples, shown in Fig 6, initiates almost immediately and behaves linearly untill failure. Failure occurs at 1.2% strain for a pristine SE samples while it fails near 0.7% strain in the OH samples showing that the MSD outlier analysis can capture the effect of pre- existing damage on the materials life. In addition, more variation in the damage curves for the OH samples was observed which could be attributed to the varying level of damage that exists from manufacturing the holes.



**Figure 6** Damage curve calculated for the thrstraight edge and open hole samples.

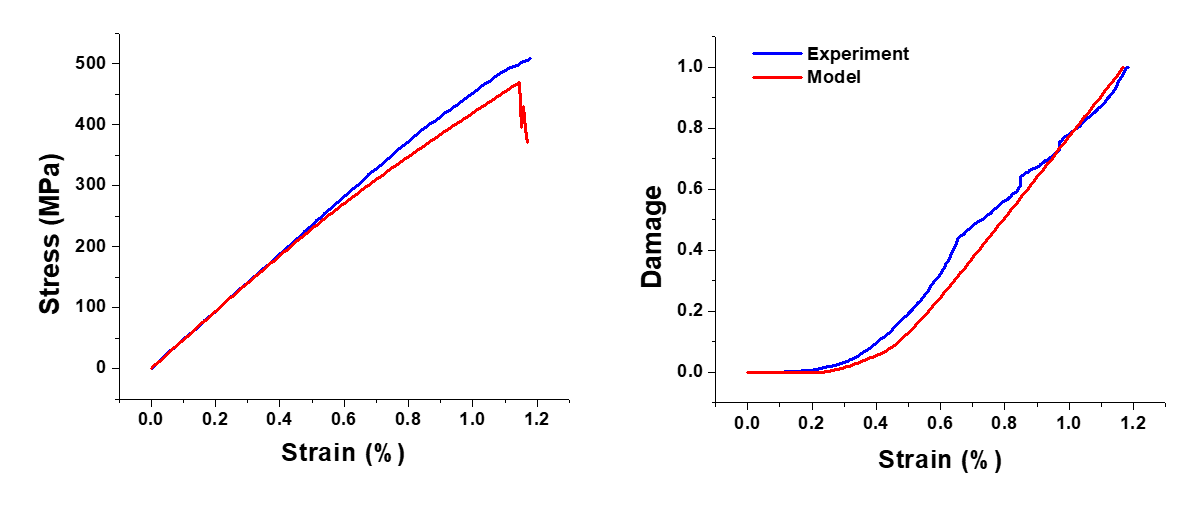
The MSD method poses itself well for the addition of information from multiple sources including DIC strain and pIRT information to increase the reliability of the damage evolution curve. The evolution of the strain from DIC provides surface evolution and damage precursor information in the form of a surface response to damage, pIRT enhances the identification of the precursors based on near surface reponse while AE can give information on both surface and subsurface damage precursors. By combining aspects of each of these tools using the same AE features as used in Fig 6, and adding the maximum strain value, the standard deviation of the strain, the maximum temperature, and the standard deviation of the temperature to the data used in the MSD calculation will produce a curve such as the one in Fig 7 overlaid with the curve calculated from AE data only. To calculate the MSD with multiphysics data, the difference in sampling rates need to be accounted for. In this case the system with the lowest sampling rate, DIC, was used as the base and the AE and pIRT data were down selected to match this rate. The value of every AE hit recorded during each second was averaged to be represented as a single point while the same was done for every pIRT frame. The result of the outlier analysis is shown in Fig 7.



**Figure 7** AE based damage degredation curve and multiphysics (AE, DIC, and pIRT) damage degredation curve.

## 3.2 Computational Modeling Results

Comparison between the simulated and actual experiments in Figure 8 (left) shows that the general behavior in terms of the stress-strain response of the composite can be captured by the assumptions made. In fact, the simulated stress-strain curve was overlaid with the test stress-strain curve and were found to be in good agreement for the initial response with some deviations observed in the later portion of this curve (i.e.. past 0.4 % strain) which is associated with the development of damage as shown in Figure 8b.



**Figure 8** (left) Stress strain curve comparison of the simulation at test data. (right) Damage degredation predicted by the model compared to the experimental result (mention it is for SE)

In a similar manner the degradation of the material predicted by the model was compared to the degradation curve developed using the AE data in Fig. 7 and were found to be in excellent agreement, as shown in Fig. 8 (right) that shows the cumulative damage as a function of applied strain. Furthermore, the type of damage and its location can be visualized using the model. Specifically, it was found that the first appearance of damage occurs in the 90 degree plies indicated by the red areas in Fig. 9. The appearance of subsurface damage matches the experimental observations in which AE activity was seen to initiate near 0.2% strain, while DIC showed surface damage initiating at almost 0.8% strain.

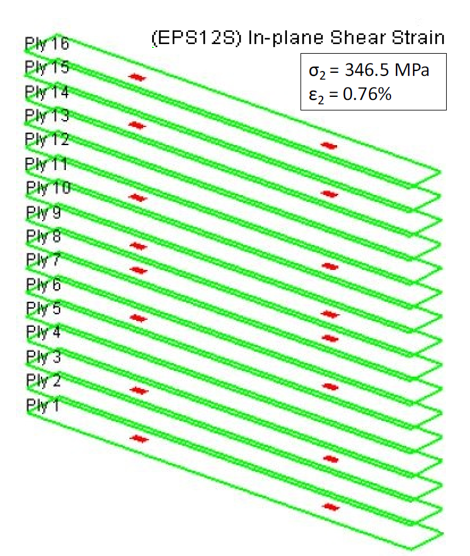


Figure 9 Visualization of damage locations in the model

4. Conclusions

An approach to calibrate a computational model using mechanical and nondestructive evaluation data related to the progressive failure of a fiber-reinforced composite was demonstrated in this article. The model is using a micromechanics model along with a number of failure criteria the activation of which produced a simulated mechanical behavior and a a cumulative damage curve that agree well with experiments. The experimental information consisted of multiphysics nondestructive evaluation data coupled with an outlier analysis to produce a damage curve that is meant to provide a way to monitor the progressive failure of such materials.

**Acknowledgments**

The authors would like to acknowledge the funding for this work provided by Army SBIR Health Conscious Structures for Zero-Maintainence Rotorcraft Platforms Phase II under contract number W911QX-15-C-0045.

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6. Appendix

The specific damage criteria listed in Table 3 are defined below.

Longitudinal tensile strength:

Longitudinal compressive strength:

Fiber crushing mode:

Delamination mode:

Micro-buckling mode:

is matrix shear modulus =

Transverse tensile strength:

Transverse compressive strength:

In-plane shear strength:

Transverse normal shear (through thickness delamination) strength:

Longitudinal normal shear (through thickness delamination) strength:

, , , , , , , , , are given in Table 1 and 2, while the fiber and void volume ratios are defined below

Reverse engineered engineered effective volume ratio of contents

|  |  |  |  |
| --- | --- | --- | --- |
|  | Symbol | Effective | Units |
| Fiber Volume Ratio | Vf | %59.34 | [-] |
| Void Volume Ratio | Vv | %2.03 | [-] |