Paper Number:

Session Topic: ***Verification and Validation of Progressive Damage/Failure Analysis for Stiffened Composite Structures***

Title: **Assessment of Intralaminar Progressive Damage and Failure Analysis Methods Using an Efficient Evaluation Framework**

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ABSTRACT

Reducing the timeline for development and certification for composite structures has been a long standing objective of the aerospace industry. This timeline can be further exacerbated when attempting to integrate new fiber-reinforced composite materials due to the large number of testing required at every level of design. computational progressive damage and failure analysis (PDFA) attempts to mitigate this effect; however, new PDFA methods have been slow to be adopted in industry since material model evaluation techniques have not been fully defined. This study presents an efficient evaluation framework which uses a piecewise verification and validation (V&V) approach for PDFA methods. Specifically, the framework is applied to evaluate PDFA research codes within the context of intralaminar damage. Methods are incrementally taken through various V&V exercises specifically tailored to study PDFA intralaminar damage modeling capability. Finally, methods are evaluated against a defined set of success criteria to highlight successes and limitations.

INTRODUCTION

Composite material integration in aircraft structures is hindered by the long timeline for development and certification. The widely accepted building block approach is limited by both time and cost as large numbers of tests are required at every stage. Adoption of new materials or expansion beyond the established design space requires further testing, which drives an endless loop of empiricism and frequently results in not exploiting the full capability of composite material in structures. The NASA Advanced Composites Consortium (ACC) seeks to develop and transition technology that will enable a reduction in the required timeline for certification of new composite aircraft structures. Pursuant to this goal is the use of

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advanced computational structural analysis techniques known as progressive damage and failure analysis (PDFA) methods. To date, various PDFA methods have been shown to predict the onset and growth of a limited number of damage modes in composites. However, the adoption of these methods within industry has been slow since the underlying material models have not yet been fully evaluated, or the methods lack technical maturity for use on production programs.

A framework was previously developed to evaluate the material models used in PDFA methods by using a piecewise verification and validation (V&V) approach [1]. In the context of finite element analysis (FEA), this framework is used to understand how material models are developed and deployed within the numeric domain on an element-by-element (or volume-by-volume) basis to represent material damage and two-piece failure. The framework subdivides the stress-strain response of a material into the elastic, pre-peak, failure criteria, and post-peak regimes. The response of a material model in a PDFA method can be verified and validated in each regime independently to establish method strengths and weaknesses. This framework is applied to evaluate PDFA method predictions for the elastic, pre-peak, and failure response of validation test specimens with an emphasis on the evaluation of CompDam [2] [3] and Enhanced Schapery Theory (EST) [4]. Both CompDam and EST are continuum damage mechanics (CDM) based research codes developed as Abaqus user-defined materials (VUMAT) [5].

In this paper, a V&V approach to assess PDFA predictive capabilities for intralaminar damage is presented. Verification exercises are initially performed by comparing predictions from unidirectional single element tension (SET) and single element compression (SEC) models against the failure envelopes used by each method. Simulation results for center notched tension (CNT) and center notched shear (CNS) specimens are then evaluated against theoretical solutions [6]. Using insight gained from the CNT/CNS simulations (e.g., mesh size requirements for accurate prediction of matrix crack propagation and an understanding of method responses for Mode I/II matrix cracks development), the formulated material model's response to combinations of in-plane shear and tension/compression loading is examined using off-axis tension (OAT) and off-axis compression (OAC) models and is compared to validation test data. Finally, lessons learned from OAT/OAC verification and validation analyses are applied to open hole compression (OHC) simulations. Results of OHC FEA are then compared to test data. Discussions on key findings from the V&V approach and lessons learned are presented, with closing remarks providing a final summary.

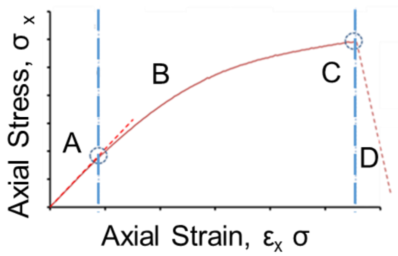
VERIFICATION AND VALIDATION FRAMEWORK FOR PDFA METHODS

The V&V process is used to evaluate the current capabilities of PDFA methods. Verification determines whether the computational model accurately represents the underlying mathematical models and assumptions; i.e., verifies that the mathematical models of the solution algorithms are working appropriately and establishes confidence in discrete solution accuracy. Validation determines whether a method accurately represents the physics of a given problem. In summary, verification evaluates functionality whereas validation evaluates physical accuracy [1].

Three key elements of the V&V approach are system response features, validation testing, and accuracy requirements. System response features define the features of interest that can be evaluated by a metric. Validation testing defines a set of tests where the predictive capability of the model is to be demonstrated. Finally, accuracy requirements specify the acceptable range of agreement between simulation results and benchmark solutions or experimental data. The features of interest to evaluate intralaminar damage capability for PDFA methods are the elastic response, pre-peak (linear or nonlinear) behavior, failure criteria, and finally post-peak behavior. When loading is initiated, the elastic response governs the undamaged stress-strain state. As the elastic response transitions to pre-peak behavior, stiffness degradation achieved through constitutive laws and/or damage parameters may initiate. This response continues with loading until a failure criterion is satisfied. Beyond this point, the stress-strain response transitions into post-peak behavior which is generally modeled with either an instantaneous stiffness degradation or a traction-separation (crack-band) based energy release for CDM based methods.

PDFA methods are formulated to have the constitutive response shown in Figure 1. Inability to appropriately capture the system response features in a physically representative manner can ultimately compound and generate errors in the overall simulation results; hence, it is necessary to first evaluate method capability via verification exercises at the element level, and then incrementally increase in simulation complexity until scaling up to validation level exercises. CompDam and EST represent each system response feature of interest with different assumptions and theories, with either a two-dimensional (2-D) or three-dimensional (3-D) formulation, as seen in Figure 1 [7]. The system response features are summarized in TABLE I and the accuracy requirement definitions for each V&V exercise considered in the present study are listed in order of increasing complexity [1]. Key findings taken from each level are carried forward to incrementally more difficult simulations in order to logically evaluate the PDFA methods.

The SET/SEC models are used to verify the matrix failure criterion for a single element subject to a range of tension, compression, and shear loading conditions (Region C in Figure 1). The CNT/CNS models are used to evaluate mode I and mode II matrix crack extension for crack-band-based degradation techniques to represent total element failure. These models provide insight into whether the formulation correlates to closed-form analytical linear elastic fracture mechanics (LEFM) solutions (Region D in Figure 1) for matrix cracks. OAT/OAC analyses assess the interactions of tension/shear and compression/shear matrix damage. These models evaluate whether a PDFA method agrees with analytical solutions for the elastic response and failure criteria (Region A and C in Figure 1). Using validation test results, quantitative and qualitative comparisons to pre-peak behavior, failure stress, and post-peak behavior is also presented (Region B, and C in Figure 1). Hence, the OAT and OAC configurations are considered both verification and validation exercises. Finally, the OHC specimen is used to evaluate whether a PDFA method captures interactions of intralaminar compression/shear matrix damage, fiber compression damage, and delamination (interlaminar) damage. Validation test results for OHC specimens are used to determine if the PDFA methods are capable of representing the material response in Regions A, B, and D in Figure 1, due to the coupled intralaminar/interlaminar damage occuring at the laminate level; thus the OHC specimen is considered a purely validation exercise.



System Response Features	CompDam	EST
A. Elastic Response	3D Elastic	2D Elastic
B. Pre-Peak	Ramberg-Osgood shear non-linearity	Schapery microdamage (tension, compression, shear)
C. Failure Criteria	LARC-04 (Stress basis)	Hashin-Rotem (Strain basis)
D. Post Peak	3D Crack band w/DGD	2D Crack band

Figure 1. CompDam and EST approaches for representing system response features.

TABLE I: V&V EXERCISES TO ASSESS SPECIFIED SYSTEM RESPONSE FEATURES

	Analysis	Elastic Response	Pre-Peak	Failure Criteria	Post-Peak
Verification	SET	-	-	Agree with analytical failure criteria within 5%	-
	SEC	-	-	Agree with analytical failure criteria within 5%	-
	CNT	-	-	-	Agree with analytical solution within 10%
	CNS	-	-	-	Agree with analytical solution within 10%
	OAT	Agree with analytical solution within 5%	-	Agree with analytical solution within 10%	-
	OAC	Agree with analytical solution within 5%	-	Agree with analytical solution within 10%	-
Validation	OAT	Agree with Test Data within 15%	Compare with Test Data	Agree with Test Data within 15%	-
	OAC	Agree with Test Data within 15%	Compare with Test Data	Agree with Test Data within 15%	-
	OHC	Agree with Test Data within 15%	Compare with Test Data	-	Agree with Test Data within 15%

All V&V analyses conducted with CompDam and EST were solved using Abaqus/Explicit and used the IM7/8552 material properties obtained from [7]. Since all exercises are considered static, quasi-static loading was maintained. Shell elements were used in EST simulations whereas CompDam simulations were run with both shell and solid elements. Nonlinear geometry was enabled for all analyses; i.e., elements were formulated in the current configuration using current nodal positions as opposed to being formulated in the reference configuration using original nodal coordinates [5]. Both PDFA methods are subject to the same success criteria for each V&V exercise.

SINGLE ELEMENT TENSION AND COMPRESSION

The objective of the SET and SEC verification exercises is to verify that a PDFA method can predict its respective matrix failure envelope at the element level. EST uses the Hashin failure criterion for both tensile and compressive matrix failure inititation predictions [4]. Matrix damage in CompDam is modeled using cohesive laws embedded within the constitutive response of the continuum [3]. The matrix failure criterion in CompDam is linked to the Benzeggagh-Kenane criterion for damage propagation, following the approach of Turon, et al. [8]. When a potential matrix crack is loaded in compression, CompDam evaluated the tractions acting on the matrix crack so as to conform to the LaRC04 failure criteria [9].

The finite element models are composed of a single element loaded in tension and compression as seen in Figure 2. A reduced integration shell element, S4R, is used for EST analyses, and a reduced integration solid element, C3D8R, is used for CompDam. CDM material properties are assigned to the element. The fiber angle orientation is varied between 0° and 90° and the axial failure stresses are extracted from each FEA. The failure stresses are then decomposed into transverse and shear stress components and are plotted against failure envelopes as seen in Figure 3.

The predicted failure envelope obtained with both methods agrees with its respective input failure envelope, as shown in Figure 3. Slight deviation between CompDam FEA predictions and LaRC04 is due to geometric nonlinearity integrated within CompDam, which is neglected in the closed-form solution for LaRC04. Geometric nonlinearity implemented in CompDam takes into account the change of the crack angle in the 2–3 plane, α, during analysis; whereas the closed-form solution for the LaRC04 failure criteria used to generate the plot in Figure 3, uses a constant value of α as an input parameter. EST is currently formulated for 2-D matrix failure governed by a bi-linear traction separation law that does not involve a crack plane.

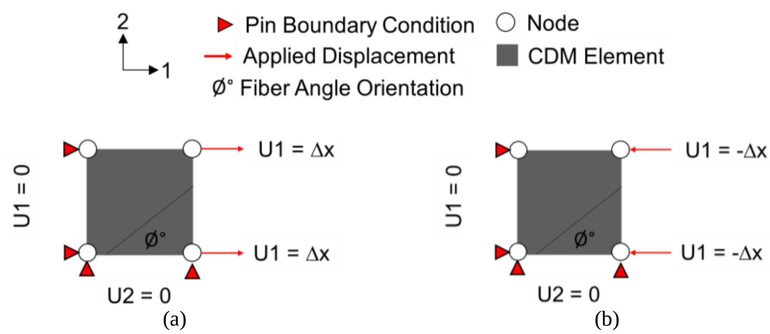


Figure 2. (a) Single element tension and (b) single element compression.

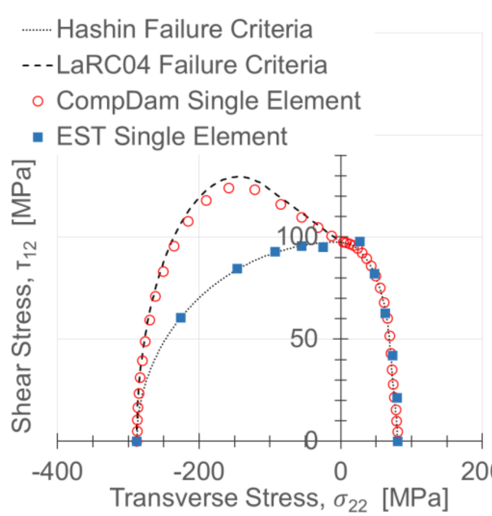


Figure 3. Failure criteria comparison for EST and CompDam.

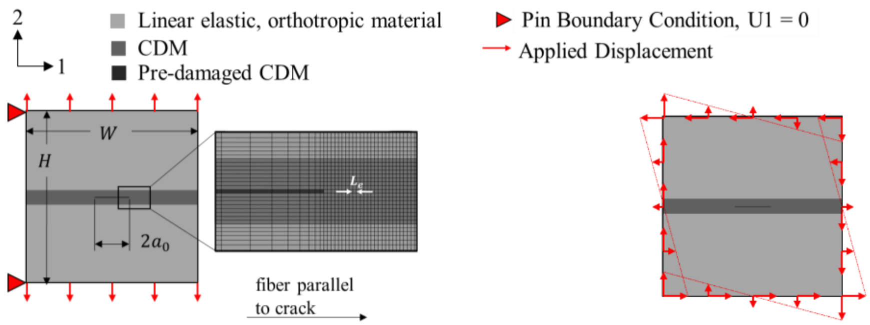
CENTER NOTCH TENSION AND SHEAR

The objective of the CNT and CNS exercises is to verify that the failure stresses obtained from the FEA agree with LEFM-based closed-form solutions for mode I and mode II matrix cracks. It is important to note that only conintuum methods that utilize the crack band approach, which ensures that the computed dissipated energy due to the fracture process is constant, for propagating total element failure, will pass these verification tests. In cases where another post-peak model is implemented (e.g., instantaneous degradation), a sensitivity study for the target application should be performed based on a method's ability to capture stress concentrations and noted failure modes.

This verification activity involves a unidirectional fiber-reinforced plate with a single central matrix crack loaded in either pure mode I or pure mode II. LEFM solutions for a unidirectional, infinite plate with a matrix crack subject to either pure mode I or pure mode II loading are used as metrics to evaluate the CNT and CNS FEA, respectively. The success criteria are defined as PDFA method agreement with the LEFM solutions within 10%. Geometry, mesh discretization, section assignments, explicit step definitions, and post-processing all follow the procedures outlined in [6] within the context of varying the element size. This activity assesses a method's ability to model the post-peak behavior as desicribed in TABLE I.

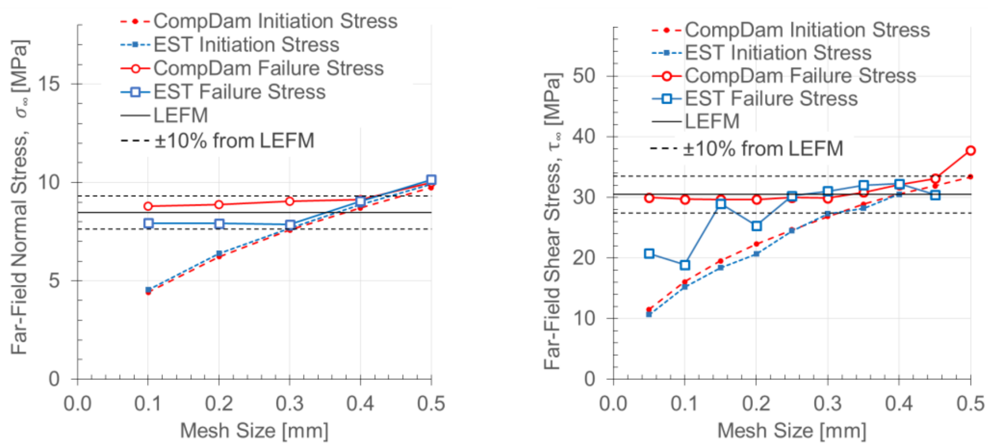
The closed-form LEFM solution for unstable crack propagation is a function of the orthotropic stiffness properties, the initial crack half-length, and the fracture toughness. The LEFM solution for the far-field normal stress, σ_∞, and far-field shear stress, τ_∞, at which the matrix crack propagates under mode I and mode II loading respectively, are defined in reference [6]. A summary of CNT and CNS FEA can be found in Figured 4(a) and 4(b), respectively. Using these models, a parametric study was conducted to determine the effect of element size in the vicinity of the initial crack on the predicted initiation and failure stresses as seen in Figures 5(a) and 5(b), respectively. For CompDam, results obtained using plane stress CPS4R elements are presented; similar behavior was observed when S4R and C3D8R elements were used. For EST, S4R elements were used. For both methods, the PDFA failure stress, the PDFA initiation stress, and the corresponding LEFM solution is presented. Failure stress is defined as the far field stress at the onset of unstable crack propagation and the initiation stress is defined as the farfield stress at the first instance of a non-zero damage variable imediately ahead of the notch-tip [6].

For the CNT case shown in Figure 5(a), increasing the element size, up to a critical element size, delays the initiation of damage. At this critical element size, the initiation stress and failure stress coincide. For larger element sizes, erroneous, mesh-dependent solutions occur; however as element size decreases, predictions from both methods converge to a plateau that is within 10% of the LEFM prediction. The critical element size for the CNT case is approximately 0.3 mm and 0.4 mm for EST and CompDam, respectively. The results for the CNS element size parametric study are shown in Figure 5(b). Like the CNT case, increasing the element size eventually leads to the damage initiation stress and the failure stress coinciding. It can be observed that predictions obtained with EST had a limited convergence to the LEFM solution, characterized by a plateau region for element sizes greater than approximately 0.25 mm. Element sizes smaller than this yielded failure stresses that deviated from the LEFM solution. In contrast to EST, CompDam solutions did converge to a plateau with decreasing element size that is within 10% of the LEFM solution. In order for both methods to agree with LEFM predictions for mode I and mode II matrix cracks 0.25 mm has been selected as the appropriate element size. Since matrix cracks are expected to be a significant intralaminar failure mechanism for OAT, OAC, and OHC specimens, this element size was carried forward throughout the rest of the study.



(a) (b)

Figure 4. Boundary conditions, section assignments, and geometry for (a) CNT and (b) CNS. W, H, and a_0 are 127 mm, 127 mm, and 12.7 mm, respectively.



(a) (b)

Figure 5. CNT (a) and CNS (b) mesh size convergence to LEFM solutions.

OFF-AXIS TENSION AND COMPRESSION

The OAT and OAC verification exercises evaluate how the PDFA methods rotate the material coordinate system in order to calculate off-axis stiffness and failure stresses. Validation test data for the OAT and OAC specimens are used to assess each method's ability to simulate the pre-peak and post-peak responses. Success criteria for verification is defined as PDFA method agreement with analytical stiffness and failure envelope stresses within 5% and 10%, respectively. Success criteria for validation is defined as agreement with test data failure stress and strain within 15%.

The OAT and OAC specimens are 25.6-mm and 38.1-mm long, respectively. Both specimens have a height, H, equal to 25.6 mm. Sections are assigned either elastic or CDM properties. The length of the CDM region is approximately 101 mm and 33 mm for OAT and OAC models, respectively. The length of the CDM region was selected based on convergence studies that minimized the effect of the CDM region length on the FE solution. Boundary conditions, geometry, and section assignments for OAT and OAC can be found in Figure 6. Each laminate is 24-plies thick and composed of all 15°, 30°, 45°, 60°, 75°, or 90° unidirectional plies. The meshing strategies employed for EST and CompDam are structured and fiber-aligned, respectively. A representation of the mesh for both methods is shown in Figure 7. CompDam encountered internal convergence issues when enabling pre-peak nonlinearity in the OAC analyses. In order to circumvent this issue, solutions with both pre-peak nonlinearity enabled and disabled are presented for OAC analyses. Pre-peak nonlinearity was enabled for all OAT CompDam analyses.

Method comparisons to test data and analytically calculated stiffness and failure envelope stresses can be seen in Figures 8 and 9, respectively. Analytical stiffness were calculated using [8] and failure envelope stresses were determined by decomposing failure stresses into transverse shear and tensile stress components. Both methods are shown in Figure 8 to agree with the analytical solutions for stiffness within 5% for both OAT and OAC models. Similar behavior can also be observed with most validation test data stiffness. The failure envelopes of test data and both methods are plotted in Figure 9 by decomposing failure stresses into transverse normal (σ_{22}) and shear stress (τ_{12}) components. EST and CompDam are shown to agree in Figure 9(a) with their respective failure envelopes within 10%; however, EST underpredicts the failure stresses for the 75° and 90° cases. This should be noted that it is not a deficiency in the code, but rather the metric of comparison between CompDam and EST. EST, as a strain-based criteria, did recover the appropriate failure strain, however, the pre-peak nonlinearity causes the failure stress to be underpredicted. It is shown in Figure 9(b) that CompDam, with pre-peak enabled, consistently under-predicts the LaRC04 envelope. Even with pre-peak disabled, CompDam slightly underpredicts the LaRC04 criteria for the 30° and 45° OAC specimens; however, EST is able to recover the Hashin failure envelope within 10% for all laminates except for the 45° OAC specimen. It should be noted that the test data largely agrees with the Hashin failure envelope for OAT; whereas for OAC, test data agreed with the LaRC04 envelope.

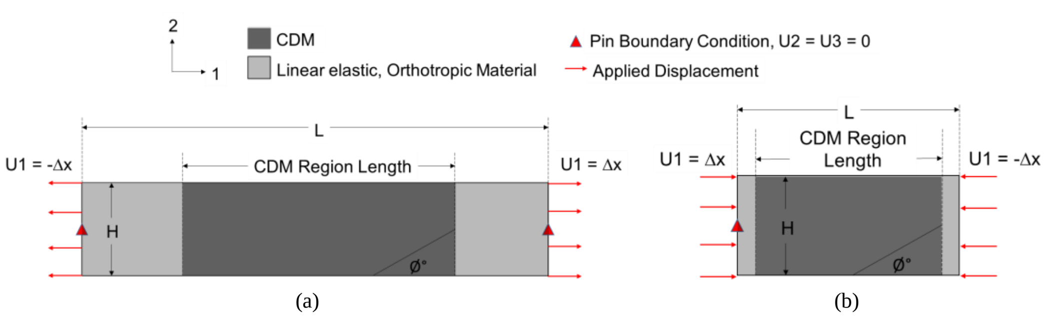
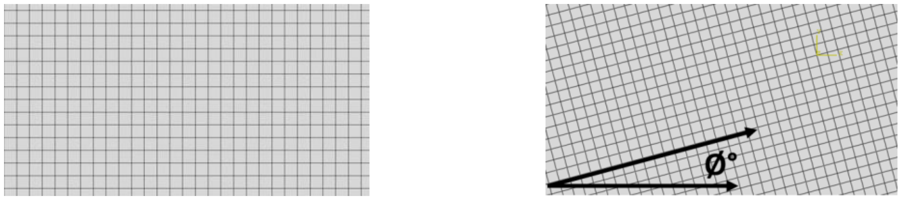
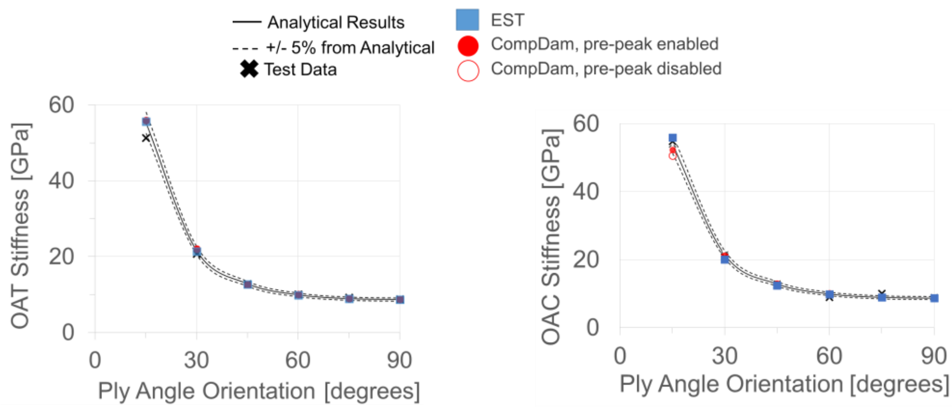


Figure 6. (a) OAT and (b) OAC boundary conditions and section assignments.



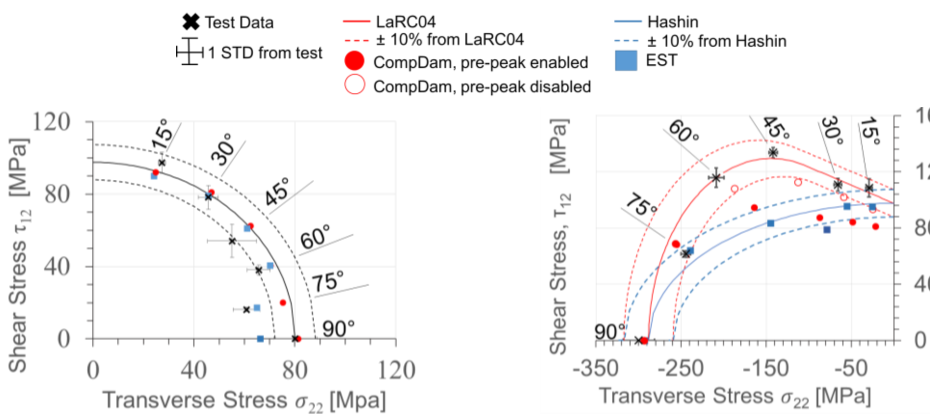
(a) (b)

Figure 7. (a) Structured mesh for EST and (b) fiber-aligned mesh for CompDam.



(a) (b)

Figure 8. Method comparison to analytical and test stiffness for (a) OAT and (b) OAC.



(a) (b)

Figure 9. Method comparison to analytical and test failure envelope for (a) OAT and (b) OAC.

The stress-strain response obtained using EST and CompDam are compared to test data for both OAT and OAC in Figures 10 and 11, respectively. It is shown in Figure 10 that CompDam fell within one standard deviation for stress and strain in all OAT models except for the 75° OAT case. This result was expected since the 75° OAT test specimen failure stress fell short of the Hashin failure envelope as seen in Figure 9 (a). EST was within one standard deviation of both average failure stress and strain for the 15° and 45° OAT tests. EST also agreed with test data failure stress within one standard deviation for all tests except for the 90° case. The results from neither method were able to fall within one standard deviation of failure strains for any OAC cases, as shown in Figure 11. Both methods fell within one standard deviation of the failure stress only for the 90° OAC specimen.

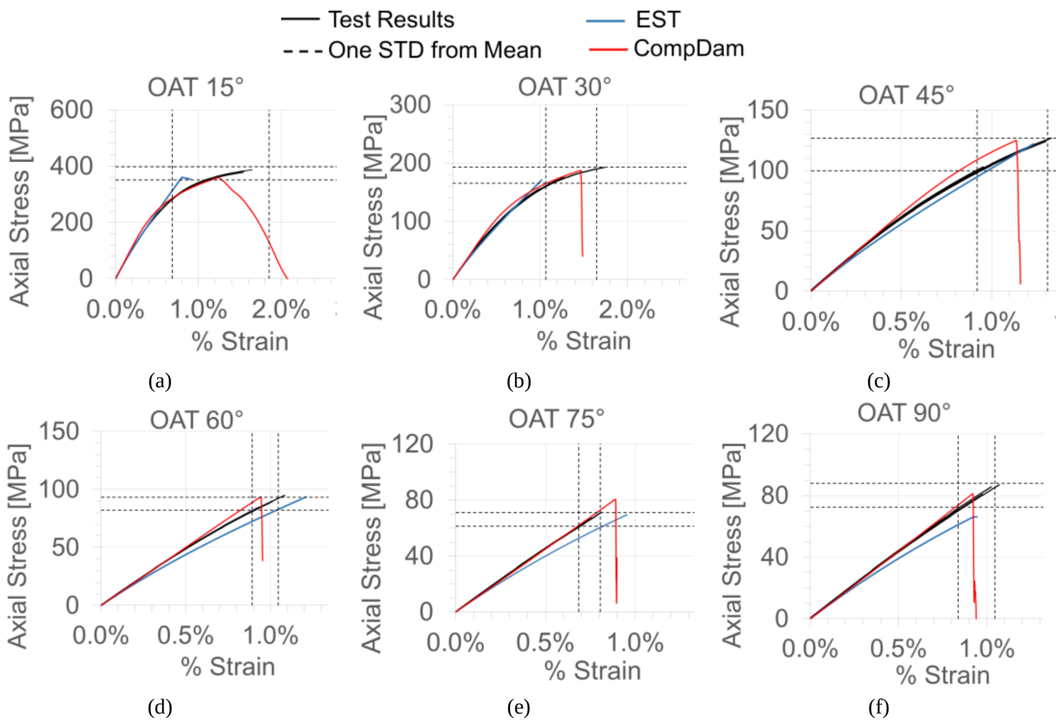


Figure 10. OAT methods comparison to validation test data.

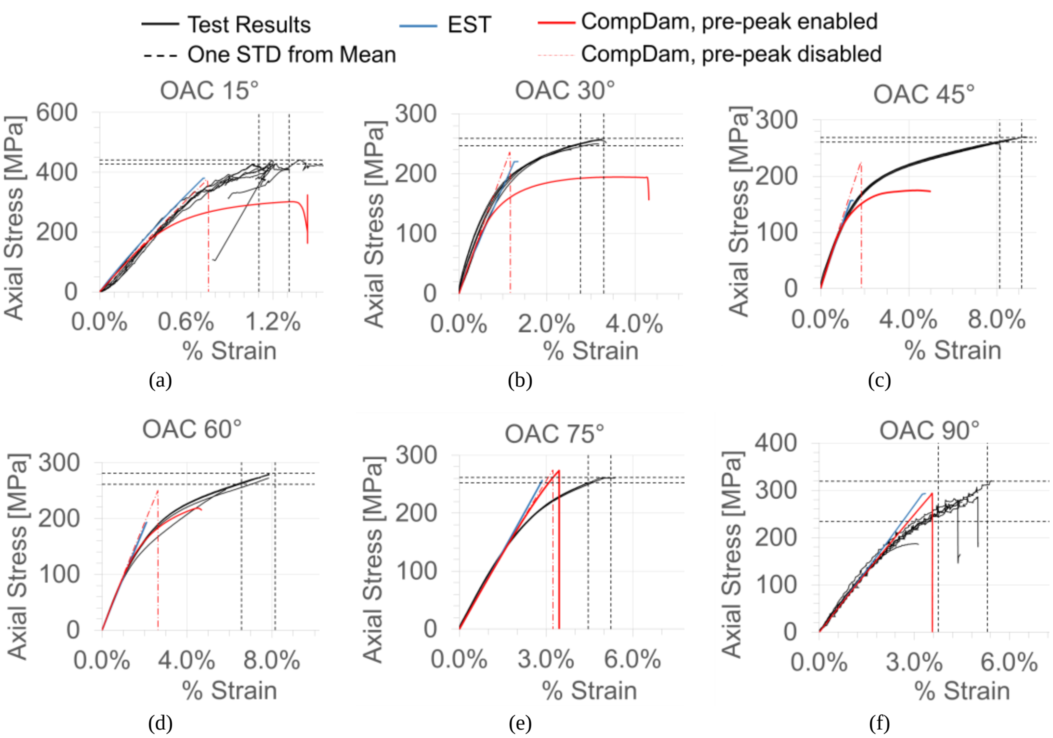


Figure 11. OAC methods comparison to validation test data.

OPEN HOLE COMPRESSION

The purpose of the OHC validation exercise is to determine whether a method can provide accurate physical representations of intralaminar compression damage when interacting with delamination. Validation test data for OHC is used to assess method ability for the pre-peak response and post-peak response. Success criteria for validation is defined as method agreement with test data failure stress and strain within 15% of test data average. One standard deviation from the test data is also presented to show variation in testing.

The length, L, of the OHC specimen is 177.8-mm long with a height, H, of 38.1 mm. Hole radius is 3.175 mm. Sections are assigned elastic or CDM properties. The length of the CDM region is approximately 55 mm. As with the OAT and OAC specimens, the length of the CDM region has been selected based on minimizing its effect on the FEA solution while still obtaining acceptable run times. Boundary conditions, section assignments, and geometry are illustrated in Figure 12. Three different laminates are considered for the OHC study: Delam, Soft, and Quasi laminates. Specific stacking sequences for each laminate is defined in TABLE II. As with the OAT and OAC exercises, EST and CompDam use different meshing strategies. A radial mesh is used with EST whereas a fiber oriented mesh is used with CompDam. These meshes can be seen in Figure 13. As with the OAT and OAC exercises, FEA involving CompDam are presented with both pre-peak nonlinearity enabled and disabled whereas FEA using EST are presented with pre-peak nonlinearity enabled.

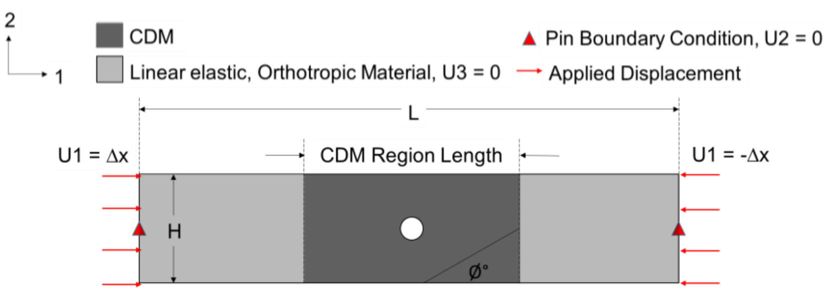


Figure 12. OHC boundary conditions, geometry, and section assignments.

TABLE II: OHC STACKING SEQUENCE

Laminate Name	Stacking Sequence
Delam	[45/-45/0/45/-45/90/45/-45/45/-45]s
Soft	[45/0/-45/90/45/0/-45/90/45/0/-45/90]s
Quasi	[45/-45/ 0/ 0/ 45/ -45/ 0/ 0/ 45/ -45/ 0/ 0]s

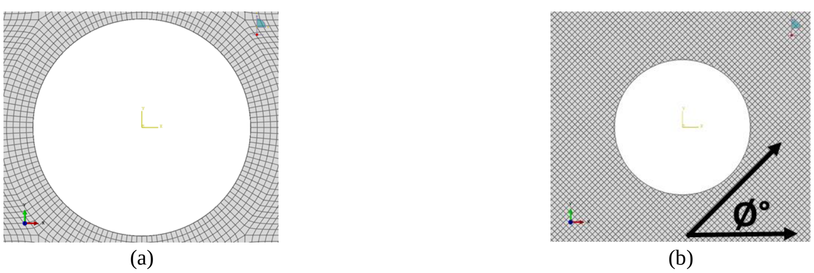


Figure 13. (a) Structured radial mesh for EST and (b) fiber-aligned mesh for CompDam.

Elastic stiffness obtained from validation test data are compared to PDFA method stiffness in Figure 14. Test data stress versus strain responses are compared directly to both methods in Figure 15. Although EST and CompDam agree with the elastic response of the test data within 5%, neither method is within one standard deviation of failure stress and strain for any of the laminates. Experimental results show that the stress and strain response of the test coupons is largely linear until failure except for the Soft case. This trend is also observed for the pre-peak responses of both methods for each laminate. EST better approximates the failure stresses for the Delam and Quasi laminates, whereas CompDam better approximates the failure stresses for the Soft laminate. Both methods consistently underpredict the failure stresses.

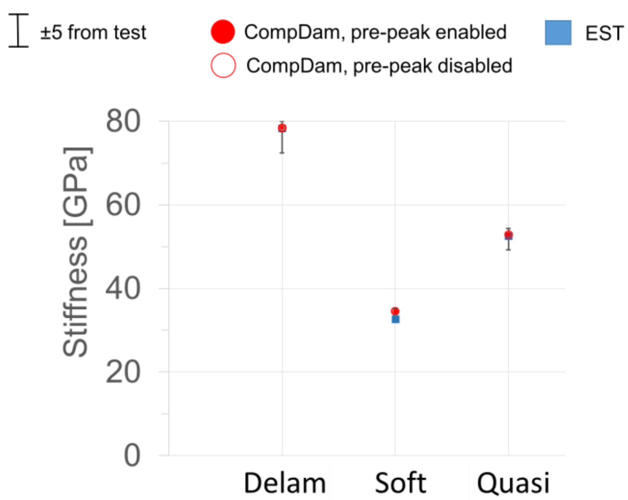
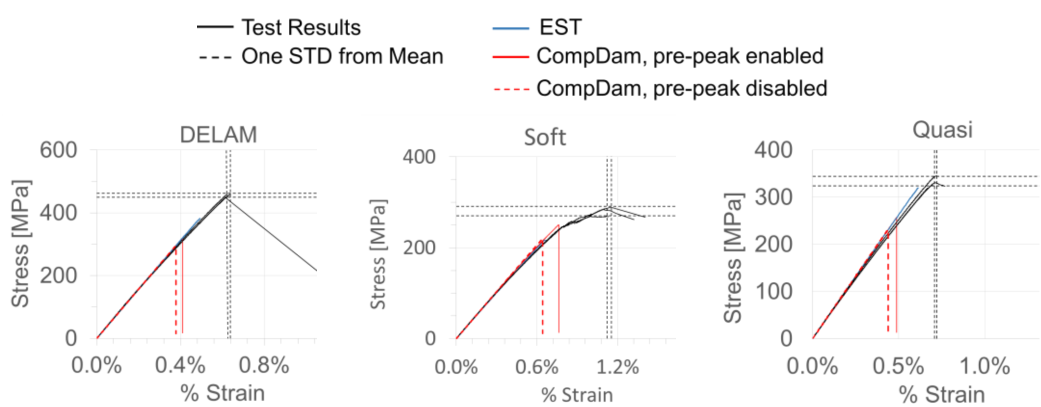


Figure 14. OHC stiffness comparison.



(a) (b) (c)

Figure 15. Validation stress-strain comparison with methods for the (a) Delam, (b)Soft, and (C) Quasi laminates.

DISCUSSION

Establishment of how the V&V framework identifies technical maturity of EST and CompDam is visualized in TABLE III and TABLE IV. Whether a method demonstrates technical maturity or if further maturity is needed for a specific verification exercise is highlighted in TABLE III. Stringency with verification success criteria is necessary since the purpose of verification is to demonstrate that the methods' mathematical models are working as-intended and to establish confidence that the discrete solutions of the mathematical models are accurate; hence a binary evaluation is used to assess the methods. How well a method can provide accurate physical representations of the validation tests is then illustrated in TABLE IV. Since variation in test data is inherent in any experiment, success criteria for the validation cases are more relaxed relative to the verification exercises; hence a three tier evaluation is implemented. Once it is determined where a method is limited in the V&V evaluation tables, it is then possible to segregate the root cause of discrepancy for each exercise.

TABLE III: METHOD TECHNICAL MATURITY FOR VERIFICATION EXCERCISES

			EST		CompDam, Prepeak Enabled		CompDam, Prepeak Disabled	
	Test Cases		Stiffness	Failure Stress	Stiffness	Failure Stress	Stiffness	Failure Stress
Verification	SET		-		-		-	-
	SEC		-		-		-	-
	CNT		-		-		-	-
	CNS		-		-		-	-
	OAT	15						
		30						
		45						
		60						
		75						
		90						
	OAC	15						
		30						
		45						
		60						
		75						
		90						

Success Criteria Met Success Criteria Not Met

TABLE IV: METHOD TECHNICAL MATURITY FOR VALIDATION EXCERCISES

			EST			CompDam, Prepeak Enabled			CompDam, Prepeak Disabled		
	Test Cases		Stiffness	Failure Strain	Failure Stress	Stiffness	Failure Strain	Failure Stress	Stiffness	Failure Strain	Failure Stress
Validation	OAT	15	8%	44%	-4%	9%	14%	-1%	-	-	-
		30	3%	44%	2%	5%	6%	4%	-	-	-
		45	-1%	16%	8%	1%	18%	10%	-	-	-
		60	-2%	22%	7%	0%	15%	7%	-	-	-
		75	-3%	27%	5%	-2%	36%	22%	-	-	-
		90	-1%	2%	-17%	-1%	2%	1%	-	-	-
	OAC	15	2%	-56%	-13%	-8%	3%	-25%	-5%	-54%	-14%
		30	-4%	-79%	-14%	0%	19%	-23%	1%	-91%	-7%
		45	1%	-136%	-52%	3%	-47%	-35%	3%	-124%	-16%
		60	10%	-88%	-38%	12%	-45%	-21%	11%	-95%	-10%
		75	-12%	-51%	-5%	-12%	-34%	5%	-12%	-40%	6%
		90	-1%	-31%	2%	-2%	-25%	-2%	-2%	-25%	-2%
	OHC	Delam	3%	-22%	-16%	3%	-35%	-30%	3%	-40%	-35%
		Soft	-2%	-41%	-23%	3%	-32%	-11%	3%	-43%	-22%
		Quasi	2%	-13%	-4%	2%	-31%	-23%	2%	-38%	-31%

< 15% of Test Data   < 20% of Test Data   > 20% of Test Data

The V&V framework illustrated that both methods successfully passed the SET, SEC, CNT, and CNS verification exercises. The success of each methods in the SET and SEC exercises established confidence that each method was able to reproduce their respective failure envelopes for intralaminar matrix damage. Success with the CNT and CNS exercises assured that the methods were able to agree with LEFM solutions for mode I and II matrix cracks for a given range of element sizes. This success allowed for implementing a fracture-based element size requirement for further intralaminar damage modeling.

The results in TABLE III and TABLE IV suggest that limited success was obtained by both methods for the OAT and OAC V&V activities. Success with OAT and OAC activities would imply that a method would be able to obtain its failure envelope for a coupon level FEA. CompDam was able to obtain its designed failure envelope in tension; however, CompDam did not agree with the compressive failure envelope when pre-peak nonlinearity was implemented. The stress and strain response in Figure 11 revealed that CompDam began to follow the same nonlinear curve as the test specimens, but tended to plateau prior to the actual failure stress; hence CompDam with pre-peak nonlinearity underpredicted the LaRC04 failure envelope. With pre-peak nonlinearity disabled, CompDam was able to fall within 10% of the LaRC04 criteria for most specimens, but still unpredicted the failure stress for the 30° and 45° OAC models. Further interrogation of the FEA revealed that there existed stress concentrations in the top and bottom corners of the models. Stress coalesced at these locations which ultimately accumulated into premature damage initiation and propagation. Including load blocks with friction contact definitions to impose the compression boundary conditions did increase the failure stress predictions; however, this increase was only accomplished by using specific friction coefficients which were dependent on the specific laminate. Selecting a frictional coefficient based on the laminate is reminiscent of steering the FEA results to better agree with data; hence it was not presented as a solution for this study. Further investigation on contact definitions with friction needs to be done in order to provide concrete reccomendations for analyses.

EST did not agree with the Hashin criteria for the OAT 75° and OAT 90° cases. This disagreement is due to the implemention of the transverse tension nonlinearity for EST during tension lacking technical maturity. It was found that the stiffness degrades at a faster rate than what is observed in testing [9]. This effect also held true in compression given that the damage for tension and compression is assumed to be identical. If this feature is disabled, better agreement with the Hashin criteria can be achieved. Since several of the predictions fell outside the range of the methods' theoretical failure envelope, the success criteria was not completely met for the OAT and OAC verification exercises. These failures suggests that the V&V framework revealed technical gaps in methods' maturity since neither method achieved the results that were intended for the verification models; at least within the context of method implementation and application for this study.

With respect to the validation exercise for OAT, test data largely agreed with the Hashin failure envelope except for the 75° OAT specimen; hence, both PDFA methods were consistently under 20% discrepancy from tests. For OAC, test data largely followed the LaRC04 failure envelope. This agreement with LaRC04, rather than Hashin, caused a discrepancy between EST and test data since EST was designed with the Hashin failure criteria. With pre-peak disabled, CompDam largely agreed within 15% for all OAC specimens except the 45° case where discrepancy was less than 20%. In regards to failure strain, neither method was able to consistently agree within 20%, implying that the shear nonlinearity models employed by each method require further technical maturity.

OHC validation tests provided a thorough assessment of a methods' capabilities for modeling intralaminar damage when interacting with delamination. The V&V framework revealed that both methods agreed with stiffness; however, neither method was able to consistently capture the failure stress and failure strain. Further investigation into the OHC test specimens revealed that matrix splits generally occurred in the stress concentrations on the 0° plies prior to two-piece failure. These discrete matrix damage events provided strain relief in the stress concentration and delayed the onset of fiber compression and two-piece failure. Matrix splits were not captured in the FEMs using either of the methods which ultimately led to premature failure predictions. Matrix damage in FEMs coalesced from the stress concentration of the hole into large contours which spread across a finite area. The discrepancy between simulation damage formation and the physical discrete damage events observed in tests is the root cause in the error observed for both methods in their respective stress-strain response. In order to get the correct physical response; it is necessary to correctly release the energy in the form of discrete matrix splitting events as observed in the tests.

CLOSING REMARKS

A V&V framework was used to evaluate the intralaminar damage modeling ability of two CDM-based material models, CompDam and EST, in order to demonstrate the methods' technical maturity. The V&V framework provided a piece by piece method evaluation of the elastic, pre-peak, failure criteria, and post-peak regimes of an element stress-strain response (i.e., Region A, B, C, and D in Figure 1). The verification exercises have been performed to evaluate the following:

1. Obtaining a method's intralaminar stress and strain failure envelopes for a single element (evaluation of Region C)
2. Modeling transverse matrix cracks loaded in pure more I and mode II and comparing the results to linear elastic fracture mechanics predictions (evaluation of Region D)
3. Obtaining a method's elastic response and intralaminar stress-strain failure envelopes for a coupon-scale test specimen (evaluation of Region A and C)

Lessons learned from the verification exercises were then translated into validation exercises that assessed:

1. Mixed-mode tension/compression loading in OAT/OAC specimens (evaluation of Region A, B, and C)
2. Intralaminar damage interactions with delaminations for OHC specimens (evaluation of Region A, B, and D)

The V&V framework highlighted potential technical gaps and suggested areas where method improvement is necessary. An important finding from the V&V framework revealed that both methods lacked technical maturity in representing the pre-peak response. Further technical refinement is necessary for both the Schapery microdamage and Ramberg-Osgood shear nonlinearity approaches in order to accurately represent the nonlinear pre-peak stress-strain response. Furthermore, method improvement could be additionally validated by utilizing digital image correlation data and computed tomography scans obtained from the validation tests. Along with method improvement, deep dives into test results also suggest potential improvement on PDFA implementation; i.e., updating the FEA based on experiments in addition to improving the material models of the PDFA methods.

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