Paper Number:

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

Title: **Verification and Validation Process for Progressive Damage and Failure Analysis Methods in the NASA Advanced Composites Consortium**

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ABSTRACT

The Advanced Composites Consortium is a US Government/Industry partnership supporting technologies to enable timeline and cost reduction in the development of certified composite aerospace structures. A key component of the consortium's approach is the development and validation of improved progressive damage and failure analysis methods for composite structures. These methods will enable increased use of simulations in design trade studies and detailed design development, and thereby enable more targeted physical test programs to validate designs. To accomplish this goal with confidence, a rigorous verification and validation process was developed. The process was used to evaluate analysis methods and associated implementation requirements to ensure calculation accuracy and to gage predictability for composite failure modes of interest. This paper introduces the verification and validation process developed by the consortium during the Phase I effort of the Advanced Composites Project. Specific structural failure modes of interest are first identified, and a subset of standard composite test articles are proposed to interrogate a progressive damage analysis method's ability to predict each failure mode of interest. Test articles are designed to capture the underlying composite material constitutive response as well as the interaction of failure modes representing typical failure patterns observed in aerospace structures.

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INTRODUCTION

Composite aircraft structures are designed and certified by extensive physical testing supported by analytical predictions. Extensive testing is used because analysis methods are unable to reliably predict the performance and failure of composite structures especially critical failure modes regarding durability and damage tolerance. This paper describes an effort executed as part of the Advanced Composite Project to evaluate existing state-of-the-art Progressive Damage and Failure Analysis (PDFA) methods, identify limitations in a capability, and enable more use of analysis in the design phase for more targeted physical testing to validate designs. Analysis models can be run in a fraction of the total time and expense required to plan, physically build, and test composite structures, thus the timeline for design can be greatly reduced. In addition, improved analysis methods enable more design variations to be evaluated early on, therefore reducing the risk of design changes being required late in the certification phase when they are more costly and time consuming.

A Government/Industry team consisting of NASA Langley Research Center, The Boeing Company, and Lockheed Martin Aeronautics was formed to execute the evaluation of PDFA methods for residual strength prediction of stiffened composite structures loaded into post-buckling. The team evaluated state of the art assessments of analysis methodologies to select the most technically mature methods to carry forward into a detailed evaluation, improvement, and validation phase. The project is broken into phases, with the Phase I efforts focused on rigorous verification and validation of the methods with limited method improvement. Importantly, the verification and validation process implemented was successful in identifying multiple key technical gaps, which motivate further program work to be addressed in Phase II of the project.

A baseline hat-stiffened panel design was developed to use for identifying the failure modes of interest under a post-buckled response and for providing designs for typical building block validation test articles. A thorough set of verification and validation test cases were developed to interrogate analysis method capability on a piecewise basis for predicting failure modes of interest in the structural panel. A series of tests were performed to generate high fidelity test data for use in validation - capturing the entire progression of damage from matrix cracking early in the loading to final failure across multiple length scales. The data was then used to evaluate computational analysis method performance so that technical gaps and areas of improvment could be identified. The specific objectives of the Phase I activities were to

- Evaluate and identify limitations in current state-of-the-art PDFA codes
- Begin refinement and maturation of PDFA codes to address selected identfied limitations
- Develop confidence in PDFA code capabilities through validation testing

The focus of this work is to present the representative composite structural element (i.e. post-buckled hat-stiffened panel), present the process by which key structural failure modes were identified, and outline the framework within which the identified failure modes were addressed to establish computational analysis method capabilities and technical gaps.

TARGET APPLICATION AND FAILURE MODES

The target application selected for this effort is an impact-damaged multi-stringer panel loaded in compression beyond the buckling limit. This panel is representative of a typical airframe structure and can potentially fail in a number of relevant ways, including skin-stiffener disbond induced by local skin buckling, stiffener crippling, skin buckling, and sublaminate buckling due to barely-visible impact damage (BVID) at the stiffener flange termination. Stiffener crippling was considered out-of-scope in the Phase I effort.

Detailed analysis was conducted to design and size a hat-stiffened panel that could be loaded well into post-buckling before ultimate failure in order for the analysis methods to be applied to predict the strength of the pristine and impact-damaged structures [1]. The skin-stiffener disbond failure mode in the post-buckling regime was targeted, and a global and local modeling strategy was used to investigate the influence of flange taper on the desired disbond failure mode in post-buckling, shown in Figure 1.

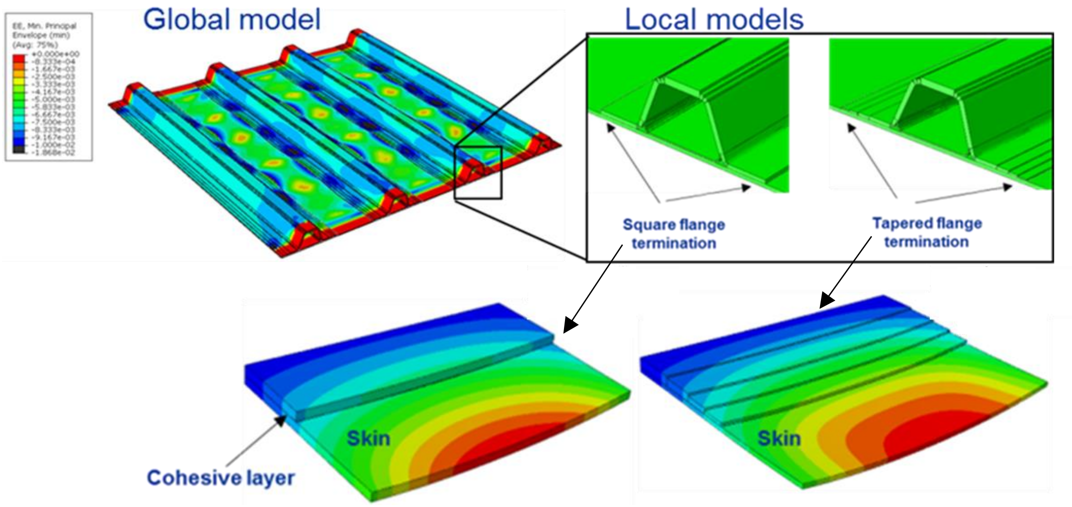

Figure 1. 4-Stringer potbuckled panel sizing

The global-local analyses identified the post-buckled performance of a panel with a tapered and square flange, as shown in Figure 2. While the results suggest better performance in strength and stiffness for a stiffened panel with a tapered flange relative to a panel with a square flange, the desired order of events for the panel response was local skin buckling, skin-stiffener disbond in the post-buckling regime, and intralaminar damage. The square flange design allowed for skin-stiffner disbonding prior to intralaminar damage development, and therefore was selected in order to provide the targeted failiure modes and failure mode interactions for PDFA evaluation and validation.

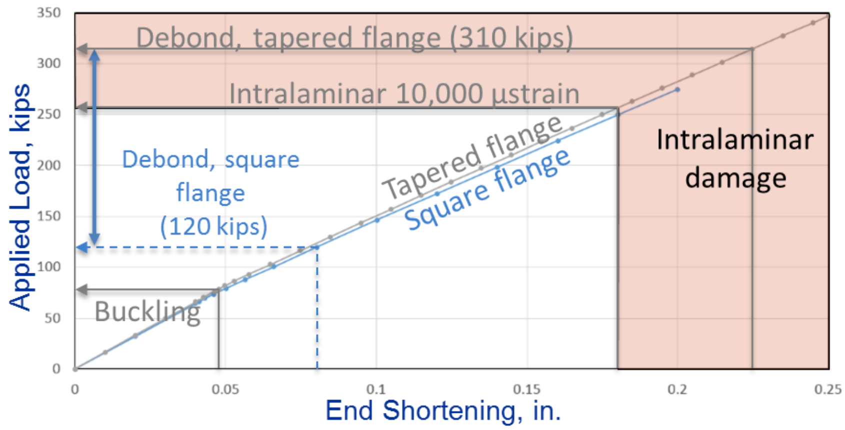

Figure 2. Comparison of predicted response of post-buckled panel with a square and tapered flange termination

Based on this general panel design, a building block validation plan was developed that includes smaller test coupons and elements that would simulate the basic failure modes expected in this type of structure, as seen in Figure 3. At the coupon level, individual specimen configurations were selected to provide the primary model validation data for critical failure modes. Laboratory scale sub-elements were selected to represent structural scale damage and failure modes at a simple level, which facilitated characterization of damage initiation and progression using advanced non-destructive inspection methods. A stringer pull-off failure mode was represented by a hat pull-off type sub-element. A three-point bend doubler specimen was included as part of the validation building block because it is one of the simplest sub-element configurations that includes many of the complicating factors of interacting matrix cracks and delaminations, which is typical of skin-stiffener separation in complex components.

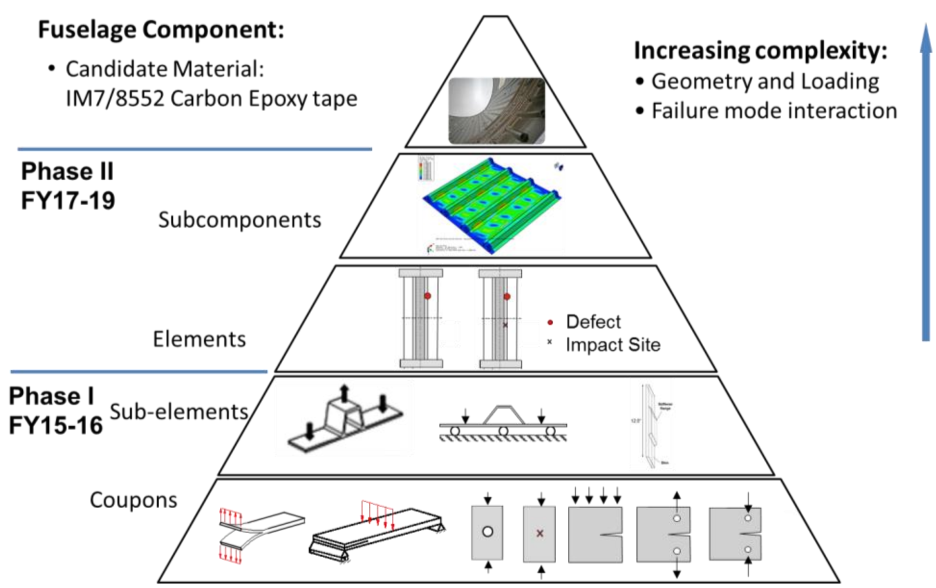

Figure 3. Validation building block

The focus of Phase I was to integrate targeted testing at the coupon and sub-element level with advanced test and inspection techniques to create a database by which methods may be evaluated. In this manner, analysis method's strengths and weaknesses were identified early in the program which guided planning for focused method developments and application in Phase II.

METHOD CLASSIFICATION, SELECTION, AND VERIFICATION BENCHMARKS

The target post-buckled panel failure modes are complex combinations of interlaminar and intralaminar mechanisms. Verification benchmark exercises were identified based on lessons-learned across multiple sources [2-9]. To determine the benchmark verification exercises for evaluating intralaminar damage predictive capability, it was first required to identify method classifications based on the scale and manner in which damage is represented.

Method Classification

The lamina level response is often represented as a continuum, as a combination and homogenization of constituents (multi-scale, homogenized multi-scale), and/or may include the ability to discretely represent damage using an enriched approach. For modeling intralaminar material behavior, a framework from [1] was used to provide rigorous correlation of method predictions to test and inspection data (Figure 4).

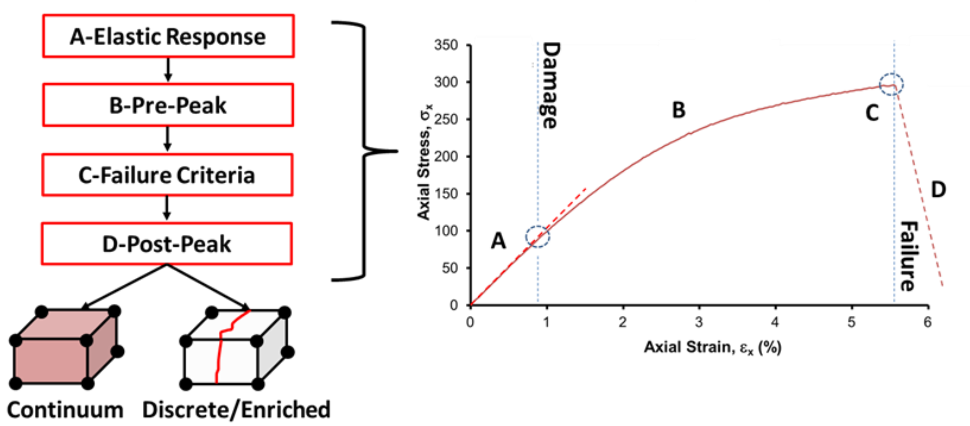

Figure 4. Framework for method evaluation based on formulation [1]

The implementation of material behavior within a finite element and/or computational analysis framework is characterized by four key responses representing the discretized region of interest at the length scale of the representative unit cell or volume element. Note: These four responses, A, B, C and D in Figure 4 and discussed below, will be referenced throughout the remainder of the paper:

A) Elastic Response: upon loading, an element will represent the undamaged elastic response based on the analysis input properties. The element will undergo elastic behavior until the initiation of damage, the progression of which is modeled by the pre-peak response (B). If the method is not formulated to include a pre-peak response (e.g. damage accumulation or nonlinear behavior within the element prior to total element failure), then the analysis may be linear-elastic until failure, which is signaled by the failure criteria (C).

   Key Consideration: What linear constitutive response is exhibited by the material?

B) Pre-Peak: the pre-peak response regards the stiffness degradation due to damage accumulation which is implemented through constitutive laws and damage parameters preceding total element failure. Total element is signaled by the failure criteria (C). Analysis methods generally include a pre-peak response in order to properly account for stress and strain simultaneously during loading to replicate material response.

   Key Consideration: What nonlinear constitutive or degradation response does the material exhibit?

C) Failure Criteria: the failure criteria signals the transition from pre-peak to post-peak (D) behavior in the element. The failure criteria initiates the complete degradation of the element and informs the nearest elements in the region of interest so that failure may be progressed.

   Key Consideration: When does the element (finite element (FE), representative unit cell (RUC), representative volume element (RVE)) fail?

D) Post-Peak: the post-peak response is governed by the method class. The post-peak response is typically implemented in the form of instantaneous degradation or energy release governed by traction-separation laws. The method class governs the fidelity to which the response is represented in the element and the region of interest (process zone development, discrete or continuum crack representation of damage events, etc.) on a failure mode basis.

   Key Consideration: How does the element (FE, RUC, or RVE) fail?

For fiber dominant layups, the laminate response may macroscopically appear to be linear elastic. As the volume of matrix dominant plies (e.g. 45s and 90s in compression) increases, the nonlinear matrix constitutive response will increasingly affect laminate scale failure. At the finite element level, the material behavior may be coded to address A, B, C, and D to meet the requirements for the existing design space, as well as investigating material responses for expanding the design space.

Selected Phase I Methods

The progject partners performed an Assessment of the State of the Art of Progressive Damage Analysis (NASA NNL10AA05B-NNL14AC05T Final Technical Report, 2015), which provided a baseline from which to evaluate method applicability for the Phase I effort. A down-selection workshop was held and the methods were evaluated based on the reported technical maturity level with respect to the noted post-buckled damage modes. Availability and feasibility to enhance the methods during the Advanced Composites Project was also assessed. Enhanced Schapery Theory (EST), CompDam, and Regularized Extended Finite Element Method (Rx-FEM) were identified for use in Phase I.

EST is a PDFA method written in the Abaqus based User Material (UMAT/VUMAT) framework [5]. EST combines an analytical model to degrade stiffness that was developed by Schapery and Sicking [6], known as Schapery Theory (ST), with an enhancement to account for failure using the crack band model. The method is formulated for use with shell sections (both continuum and conventional shells) and works with S4 and SC8 element types. ST was developed by Schapery and Sicking as a thermodynamically based work potential that accounted for the nonlinear behavior of composite materials as a result of in-plane damage. The key assumption for this work is that matrix micro-damage, characterized by micro-cracks, transverse cracking, shear banding, micro-fissure growth, and other damages, is entirely responsible for the nonlinear response of composite materials. Different modeling techniques are available to combine the in-plane EST method with out-of-plane delamination methods. EST has previously been deployed with cohesive elements, however, the zero thickness Discrete Cohesive Zone Model (DCZM) is currently in use by the developers. The DCZM is implemented as a two-parameter traction separation law. The two parameters are the cohesive strength and strain energy release rate. This requires six total inputs, two for each mode of fracture. Additionally, the user needs to prescribe a penalty stiffness to load up to the cohesive strength. The DCZM is written as an Abaqus User Element.

CompDam is a PDFA software suite that is implemented via a UMAT/VUMAT within Abaqus/Standard and Abaqus/Explicit Finite Element Solvers [7, 8]. CompDam was developed as a research code in NASA Langley Research Center for predicting damage initiation, progression, and material failure for laminated composites. Composite damage modes (i.e., matrix cracking, fiber breaking and fiber kinking) are incorporated within a Continuum Damage Mechanics (CDM) framework where the LaRC04 failure criteria is used to predict the onset of intra-laminar damage. Once damage initiates, matrix and fiber damage evolution occurs with constitutive damage models formulated with respect to the damage variables of each constituent. Matrix tensile and compressive damage is modeled by an embedded cohesive interface within an element to represent matrix cracks using deformation gradient decomposition. The embedded crack is modeled by cohesive laws and the mixed mode behavior of the matrix crack is defined using the Benzeggagh Kenane law for both intralaminar and interlaminar modes. Fiber tensile and compressive damage is modeled using a bilinear softening law.

Rx-FEM is a standalone PDFA computational analysis tool for mechanical modeling of composite materials [9, 10]. Rx-FEM is also known by the name of B-Spline Analysis Method (BSAM). The foundation of Rx-FEM is based on the extended finite element method (X-FEM). The step function that is typically used in X-FEM based approaches, the Heaviside function, is regularized for a continuous function across the crack face in the Rx-FEM approach. Additionally, the original Gauss integration scheme is preserved for any crack orientation, as opposed to adding Gauss points based on the crack and crack orientation. Rx-FEM is capable of running loading cases that include tension, compression, impact, fatigue, contact and thermal analyses. Mesh creation is done outside of Rx-FEM and is typically performed in Abaqus. The elements required are limited to 3D hexagonal type finite elements, with non-reduced integration points. Rx-FEM is capable of predicting three common failure modes: matrix cracking, delamination, and fiber failure. Matrix crack propagation is predicted using a cohesive zone method (CZM). Crack initiation is signaled using the LaRC04 failure criteria, although others are available. Delamination and fiber failure are predicted using CZM and continuum damage mechanics, respectively. Cracks and crack paths are able to be customized. Straight, non-straight cracks, predetermined crack paths, finite crack lengths, and crack spacing are parameters within Rx-FEM. To account for non-linearity in the response of a material, a nonlinear shear function can be implemented. The framework was applied to identify method components for piecewise evaluation as shown TABLE I.

TABLE I. METHOD COMPARISON BASED ON FORMULATION

Intralaminar Static					
Method	**Class**	**A**	**B**	**C**	**D**
CompDam	Continuum Lamina	3D Elastic	Matrix shear nonlinearity (Ramberg-Osgood for 1-2 plane)	LARC-04 (stress)	3D crack-band w/ deformation gradient decomposition (energy-based)
Enhanced Schapery Theory	Continuum Lamina	2D Elastic	Schapery microdamage for 1-2 plane (tension, compression, and shear matrix modes)	Hashin 2D (strain)	Crack-band (energy-based)
Rx-FEM	Enriched	3D Elastic	Matrix shear nonlinearity (IPS tabulated data for 1-2 plane)	LARC-04 (stress)	Mesh Independent Cracking (energy-based)

Verification Benchmarks

Interlaminar modeling techniques were benchmarked according to guidelines provided by Krueger [11-14]. In order to accurately predict the initiation and propagation of interlaminar damage modes, it is proposed that the in-plane (intralaminar) response must be well modeled such that the 3D stress-strain state is well correlated to the material behavior. The piecewise verification of method performance provides the opportunity to rapidly and practically determine the desired approaches to be carried forward for evaluation and validation by test and inspection data.

The verification process for the Phase I program addressed the following key tasks: (1) identify required input properties, (2) identify verification parameters, (3) perform verification analysis.

Step 1 – Identify Required Input Properties

Properties for the IM7/8552 tape material system were determined based on NCAMP testing [15] and by testing performed under a NASA study contract [1]. Properties used by EST and CompDam are provided in TABLEs II-V. Properties required by Rx-FEM are common to both methods.

TABLE II. COMMON INPUT PROPERTIES (2D)

		PROPERTY	VALUE	UNITS
Common to EST and CompDam		ply thickness	0.183	Mm
		fiber volume fraction	59.1	%
		Density	1.57E-09	tonne/mm^3
	In-Plane Elastic Constants	E_{11}^T	152,689	MPa
		E_{11}^C	140,653	MPa
		E_{22}	8,703	MPa
		η_{12}	0.32	-
		G_{12}	5164.0	MPa
	Toughness	G_1^T/Fiber	205	kJ/m^2
		G_1^C/Fiber	61	kJ/m^2
		G_1^T/Matrix	0.24	kJ/m^2
		G_1^C/Matrix	0.24	kJ/m^2
		G_{II}^C/Matrix	0.739	kJ/m^2
		G_{III}^C/Matrix	0.739	kJ/m^2

TABLE III. COMPDAM SPECIFIC PROPERTIES

		PROPERTY	VALUE	UNITS
CompDam Properties	Stiffness	E_{33}	8703.0	MPa
		G_{13}	5164.0	MPa
		G_{23}	3001.0	MPa
		η_{23}	0.450	-
		η_{13}	0.320	-
	Strength	X_{11}^T	2326.2	MPa
		X_{11}^C	1730.6	MPa
		Y_{22}^T	80.1	MPa
		Y_{22}^C	288.2	MPa
		S_{12}	97.6	MPa
		f_{XT}	0.2	-
		f_{GXT}	0.5	-
		f_{XC}	0.2	-
		f_{GXC}	0.5	-
	Shear Non-linearity	Alpha	4.06E-09	-
		N	5.4	-
	Other	alpha0	0.925	radians
		coefficient of friction	0.3	-
		CTE11	-5.50E-06	/degC
		CTE22	2.58E-05	/degC

TABLE IV. EST SPECIFIC PROPERTIES

		PROPERTY	VALUE	UNITS
EST	Failure Strain	e_{11}^{T}	0.01523	mm/mm
		e_{11}^{C}	0.0123	mm/mm
		e_{22}^{T}	0.0092	mm/mm
		e_{22}^{C}	0.0350	mm/mm
		e_{12}	0.0273	mm/mm
	Schapery Theory Properties	e_s^0	1.0	$MPa^{(-1/3)}$
		e_s^1	-6.58E-01	$MPa^{(-1/3)}$
		e_s^2	1.08E-01	$MPa^{(-1/3)}$
		e_s^3	0.0	$MPa^{(-1/3)}$
		e_s^4	0.0	$MPa^{(-1/3)}$
		e_s^5	0.0	$MPa^{(-1/3)}$
		g_s^0	1.0	$MPa^{(-1/3)}$
		g_s^1	-9.51E-01	$MPa^{(-1/3)}$
		g_s^2	2.46E-01	$MPa^{(-1/3)}$
		g_s^3	1.87E-02	$MPa^{(-1/3)}$
		g_s^4	0.0	$MPa^{(-1/3)}$
		g_s^5	0.0	$MPa^{(-1/3)}$
	DCZM Cohesive Properties	Mode I initial stiffness	2.00E+04	MPa/mm
		Mode II initial stiffness	2.00E+04	MPa/mm
		Mode III initial stiffness	2.00E+04	MPa/mm
		Mode I maximum traction	80.1	MPa
		Mode II maximum traction	97.6	MPa
		Mode III maximum traction	97.6	MPa

TABLE V. COHESIVE PROPERTIES

		PROPERTY	VALUE	UNITS
Cohesive Properties	Interlaminar	Mode I Penalty Stiffness	4.76E+05	MPa/mm
		Mode II Penalty Stiffness	2.29E+05	MPa/mm
		Mode III Penalty Stiffness	2.29E+05	MPa/mm
		Mode I Strength	80.1	MPa
		Mode II Strength	97.6	MPa
		Mode III Strength	97.6	MPa
		B-K exponent	2.07	-

Step 2 – Identify Verification Parameters

The verification parameters are determined by first identifying the reality of interest and developing the mathematical model requirements. The mathematical model is then implemented into the finite element (or other platform) via coding. Performance benchmarks for physical modeling (boundary conditions, element type, mesh strategy used/discretization, and global-local strategies) and mathematical modeling (elastic, damage, and failure parameters) are set based on the region of interest.

Step 3 – Perform Verification Analysis

The first step to performing verification analysis is to evaluate the relationships modeled in Step 1 for input equals output. This step is required to determine if the relationships have been implemented correctly into the region of interest, and does not require experimental data. Exercises to determine global-local techniques, scalability, boundary conditions, etc., may be performed and evaluated in terms of computational efficiency, processing requirements, and input equals output error. The length scale at which the models are expected to predict material response is also considered to concurrently identify the requirements for test and inspection validation data.

The Phase I verification benchmarking exercises are listed in TABLE VI. Further details regarding the benchmark analysis cases are provided in [1, 16-21].

TABLE VI. VERIFICATION BENCHMARK EXERCISES

Verification Case	Objective	Metric
0^o Tension	Verify selected methods recover strength and stiffness inputs and examine mass scaling effects, damage region size, and global-local strategies	Strength
		Stiffness
90^o Compression	Verify selected methods recover strength and stiffness inputs and examine mass scaling effects, damage region size, and global-local strategies	Strength
		Stiffness
DCB	Verify delamination implementation technique replicates benchmark solution for Mode I interlaminar fracture and evaluate mass scaling	Benchmark
ENF	Verify delamination implementation technique replicates benchmark solution for Mode II interlaminar fracture and evaluate mass scaling	Benchmark
Mixed Mode Bending	Verify delamination implementation replicates benchmark solution for mixed mode interlaminar fracture and evaluate mass scaling	Benchmark
Center Notch Tension	Verify that crackband model reproduces LEFM solution for Mode I intralaminar fracture and establish element size	10% of LEFM Solution
Center Notch Shear	Verify that crackband model reproduces LEFM solution for Mode II intralaminar fracture and establish element size	10% of LEFM Solution

VALIDATION TEST ARTICLES

Once acceptable performance was established for the exercises in TABLE VI, the PDFA methods were evaluated by comparison to validation test and inspection data. Benchmark success criteria were used to quantify the accuracy of model predictions based on experimental data confidence, and the results were used to establish acceptable agreement on performance. In this manner, accuracy, time, resource requirements, scalability, etc. may be evaluated to determine the required engineering solution.

The Phase I effort encompassed coupon and sub-element scale representations of the desired material damage and failure modes which are expected to be present at the element and subcomponent panel scales in Figure 3. The coupon and sub-element validation tests were strategically selected to characterize pre-peak behavior constitutive response and failure progression to provide required validation data. The priority validation cases are briefly described below.

Off-Axis Tension and Compression

Off-axis tension (OAT) and off-axis compression (OAC) specimens were developed to characterize the matrix-dominated intralaminar response (1-2 and 2-3 material planes) for the IM7-8552 tape system. The specimen geometries and loading conditions were selected to achieve interaction of matrix tension (transverse normal tension), matrix compression (transverse normal compression) with in-plane and through-thickness shear.

The objective of the OAT/OAC tests is to provide a validation data set for intralaminar matrix-dominated material degradation (Region B), failure criteria (Region C), and to identify meshing strategies, and global-local scalability using simple specimen configurations.

Open Hole Compression

Open hole compression (OHC) specimens were considered to provide a validation data set at the multi-ply level in which intralaminar damage modes interact with interlaminar damage modes in the presence of a notch. Three layups were selected in order to provide a range of expected specimen behavior based on relative constituent contribution. The first layup, termed "Soft", was selected because it is expected to include relatively large nonlinear response to loading due to the inclusion of multiple 45° plies. The second layup, termed "Quasi" is a quasi-isotropic layup and is similar to the skin of the 4-stringer panel to be used in Phase II of the program. The last layup, termed "Delam" was selected to try to maximize the interlaminar delamination damage mode.

The objective of the OHC test and inspection was to provide the validation data by which fundamental failure mode initiation and interaction may be correlated to analysis predictions.

3-Point Bend (Doubler)

The 3-point bend test was developed to provide a validation data set in which intralaminar and interlaminar damage modes may interact in the presence of a flange termination. The primary failure mode will be delamination which may interact with intralaminar matrix cracking at the sub-element scale.

The objective of the 3-point bend test was to integrate intralaminar and interlaminar damage modeling and validate predictions based on initiation and propagation events.

Hat Pull-Off

The hat pull off configuration was developed to provide sub-element level validation data for the interaction of interlaminar and intralaminar damage modes. The primary failure mode will be delamination which may be influenced by intralaminar matrix failures in the skin.

The objective of the hat pull-off test was to integrate intralaminar and interlaminar modeling strategies and validate at the sub-element scale predictions based on damage initiation and propagation events.

Compression Strength After Impact

The compression strength after impact (CSAI) configuration was selected to provide a coupon level validation data set wherein the complex interaction of intralaminar and interlaminar damage modes may interact under loading prior to ultimate coupon failure.

The objective of the CSAI test was to evaluate modeling implementation and method capabilities developed from off-axis, open hole compression, and 3-point bend specimens, and integrate to predict residual strength of simple impacted panels.

Summary of Validation Testing

A summary of the experimental data sets that are used for the validation exercise is provided in TABLE VII. The following data sets are considered for validation: global/local measurements such as load vs displacement, full-field displacement measurements, stiffness measurements, and strain measurements. In addition, the predicted damage shape and size are compared using non-destructive inspection techniques such as digital photos, ultrasonic inspection (UT) and X-Ray computed tomography (CT).

TABLE VII. INSPECTION TECHNIQUES FOR DAMAGE CHARACTERIZATION

Test Cases	Global/Local Measurements		DAMAGE IMAGING		
	Load vs Displacement	**Stress (or Load) vs Strain (DIC)**	**Digital Photos**	**Ultrasonic**	**CT**
OAT OAC	Global response	Tension/compression strain in near/far field	In-plane and through-thickness	N/A	N/A
OHC	Global response, initial stiffness, ultimate failure	Compressive strain	Post-mortem	N/A	75% and 90% of ultimate load
CSAI	Global response	Compressive strain	Post-mortem	Delamination shape	75% and 90% of ultimate load
3-Point Bend	Initial load drop and corresponding displacement, stiffness	Compare tensile strain at 0.5 inches from flange edges.	N/A	Delamination shape	Interface, size and shape; matrix cracks
Hat Pull Off	Global response	Near and far-field strain	Side-view crack growth	N/A	Delamination size/shape

The verification and validation building block is shown in Figure 5. At the base of the figure, the supporting intralaminar and interlaminar verification benchmarks are identified as precursors to running the specified validation analysis. The methodology is further reduced to illustrate the piecewise verification and validation in terms of the ABCD framework, and is presented in Figure 6. Further details regarding the supporting validation analysis performed are provided in [16-20].

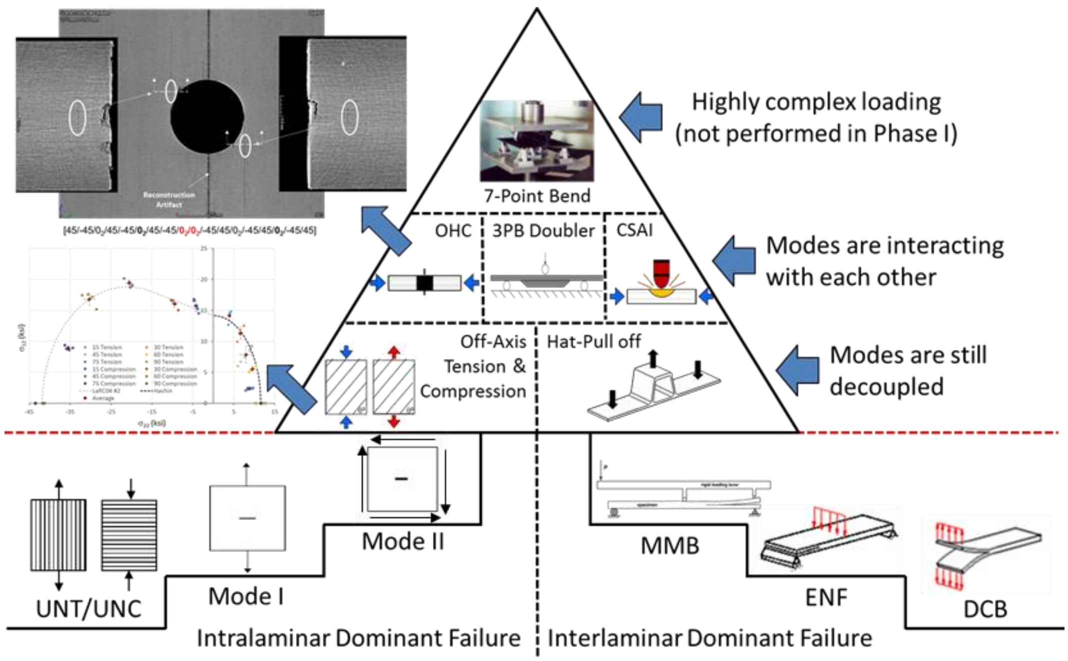

Figure 5. Verification and validation building block for piecewise analysis evaluation – analysis cases

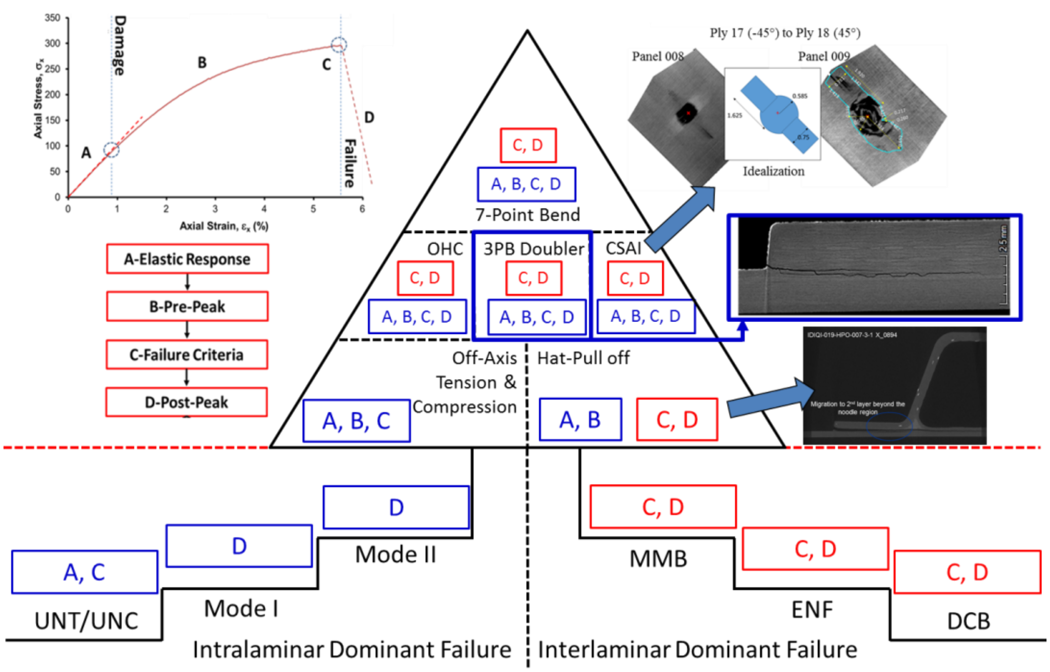

Figure 6. Verification and validation building block for piecewise analysis evaluation – analysis components

DISCUSSION AND SUMMARY

The PDFA method verification and validation approach developed for the Advanced Composite Consortium has been presented. The target application of compressive loading of a post-buckled, impacted hat-stiffened panel has been introduced and expected failure modes have been identified. A verification and validation building block approach has been constructed to evaluate selected PDFA methods in appropriately modeling the expected failure modes. Supporting verification benchmarks and validation testing for PDFA method evaluation has been established through the building block approach in order to determine method successes and method development opportunities.

The specific objectives of the Phase I of this effort were to evaluate and identify limitations in current state-of-the-art PDFA codes, begin refinement and maturation of PDFA codes to address selected identfied limitations, and finally develop confidence in PDFA code capabilities through validation testing. Furthur work extending this paper will be presented summarizing the Phase 1 activities.

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