An Overview of the NASA Advanced Composites Consortium High Energy Dynamic Impact Phase II Technical Path

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Advanced composite structures are increasingly becoming the norm for use in military and commercial aircraft. Many of these structures are in places that are prone to high energy dynamic impact (HEDI) such as a wing or fuselage structures subjected to bird strike or a fan blade out event. Certification testing is expensive and industry currently lacks to the tools to perform reliable certification by analysis or smarter testing. As such, the NASA Advanced Composites Consortium HEDI team was formed with representatives from aerospace original equipment manufacturers, government research laboratories, and academia to advance the state-of-the-art in emerging progressive damage and failure analysis (PDFA) methods in a two phase program. These PDFA approaches have the ability to predict ply-by-ply level damage in composite structures, but to date, have not been thoroughly vetted for HEDI events. In this paper, the technical path that is used in Phase II of the program is presented.

I. Introduction

The NASA Advanced Composites Consortium (ACC) seeks to develop analytical methods and tools to enable smarter testing and reduce the number of required tests for advanced composite structures prior to certification. As part of the program, consortium research teams (CRTs) were developed to examine specific challenges for which the aerospace industry desires reliable, predictive tools. A CRT was formed to examine the needs of these analysis methods and tools for high energy dynamic impact (HEDI) applications such as engine containment for an aircraft experiencing a fan blade-out event or bird strike. The goal of the team is to develop predictive tools that scale with the needs of industry to address the costs associated with element, sub-component, and component testing [1].

In Phase I of the program, NASA Glenn Research Center (GRC), Boeing, Pratt & Whitney, and General Electric Aviation partnered to examine the state-of-the-art for emerging progressive damage and failure analysis (PDFA) methods [2]. Included in these methods were LS-DYNA MAT162 [3], MAT261 [4], Smoothed Particle Galerkin (SPG) [5], and EMU Peridynamics (PD) [6] for a number of different material forms including tape, plain weave, and braided material systems. Phase I completed in 2017 and many technical gaps were observed to be addressed in Phase II.

In Phase I of the program, the team began with two main goals to address the technical challenge (Figure 1).

1. Generate realistic, high fidelity test data that is not generally not captured during typical testing to validate tools, but is representative of in-service applications. This high fidelity data may also not necessarily be gathered during certification testing either.

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2. Validate the material models that were selected for analysis approaches using objective validation data that is generally lacking in the field. Objective databases for validation of advanced analysis methods do exist [7], [8], [9], [10]; however, an equally sizable dataset for HEDI does not.

The program was designed with the goal to equally invest resources in both objectives. To accomplish the first goal, a flexane impactor was used in both a blunt and a sharp configuration. The blunt configuration was a generic right cylinder shot by a gas gun. The sharp configuration added a titanium insert embedded in the front of the blunt impactor. These impactors were representative of a typical fan blade root and fan blade leading edge, respectively. To supplement the testing, high speed photogrammetry was used to track the displacement of the panel as it was subjected to impact. After testing, through thickness ultrasonic (TTU) scanning was performed to determine the damage extent within the composite. This data would be used to validate the PDFA simulations.

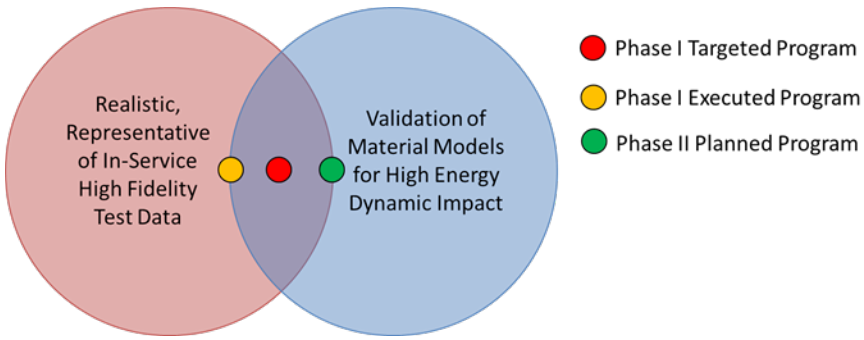

Figure 1. Phase I and Phase II planned programs

At the completion of Phase I, the complex flexane impactor behavior in both the sharp and the blunt configuration proved too difficult to replicate to conclusively validate the models. As a result, the executed Phase I program was not able to fully validate the material models. Material models were able to be calibrated and show success over a limited area; however, technical gaps with the methods were identified (Table 1).

Table 1. Noted technical gaps with methods selected in Phase I

LS-DYNA MAT162	LS-DYNA MAT261	EMU Peridynamics
Requires robust calibration scheme w/ significant effects on predictive capability	Element stability under large deformation	Projectile is not as mature as that used in DYNA approaches
Constant pressure elements (Single integration point)	Lack of modulus hardening	Difficulties comparing damage states to test data
Strain rate capabilities are highly coupled	Non-physical coupling of SOFT/PFL for high-energy thru-thickness response	Non-linear state-based peridynamics
Lacks shear non-linearity seen in modern aerospace composites	Scalability concerns due to element sizes	No high strain-rate capability

In this paper, the technical approach for the NASA ACC HEDI team for Phase II is outlined. The Phase II CRT includes Phase I members of NASA GRC, Boeing, and Pratt & Whitney and added Wichita State University and The McNAIR Center at the University of South Carolina. This technical approach developed by the CRT includes a general approach to develop material models, verify that the material models are working as expected, and validate the model and modeling approaches through a building block approach. Along the way, the noted technology gaps identified in Phase I will be addressed.

II. Technical Approach

The Phase II effort focuses on a technical approach that includes five main aspects (Figure 2):

Development of material models

1. Verification of the material models
2. Define modeling strategy
3. Validation testing
4. Assessment of technical gaps

The following subsections address critical aspects of the Phase II approach.

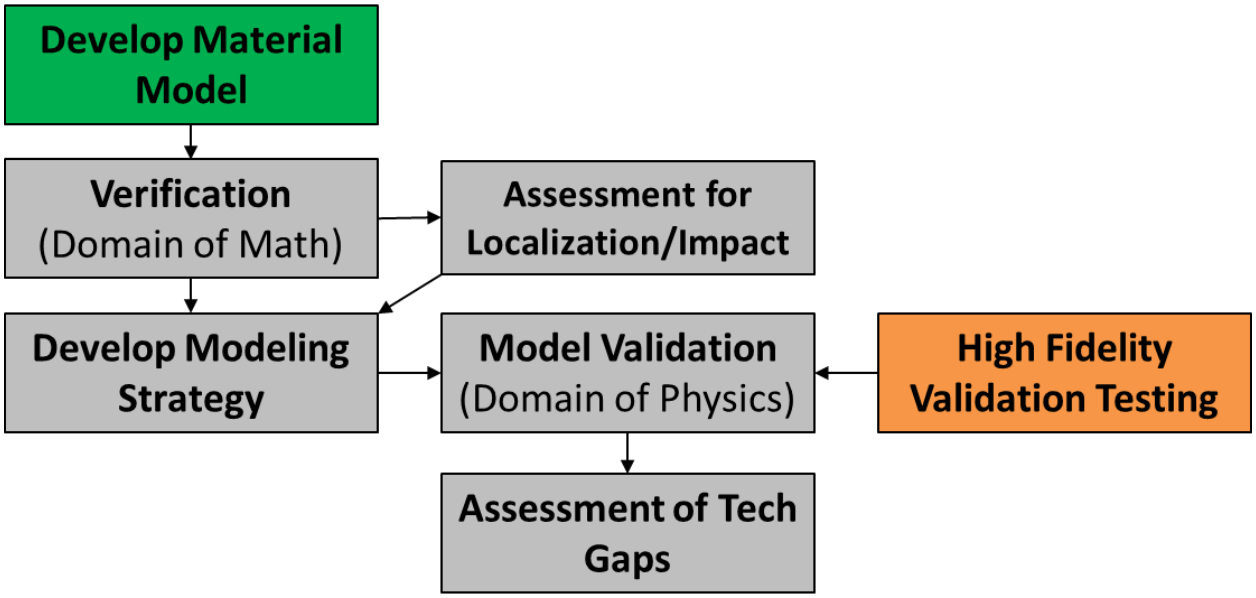

Figure 2. Technical pathway for Phase II

Development of Material Models

Each of the selected methods from Phase I were identified as having tech gaps that would need to be closed in order to improve the method for use with a generic problem (e.g. to improve predictive capability). In order to improve the material models, it was first necessary to understand the material model formulation of each of the approaches. To examine this, the ABCD framework proposed by Schaefer and Razi [11] is considered. This framework allows for comparison of methods based on method class (discrete/enriched, continuum) and length scale of interest (fiber/matrix, lamina, or laminate) by considering a general material model response for the failure mode of interest. The Schaefer model is developed by considering the piecewise contribution of each method to the overall assessment.

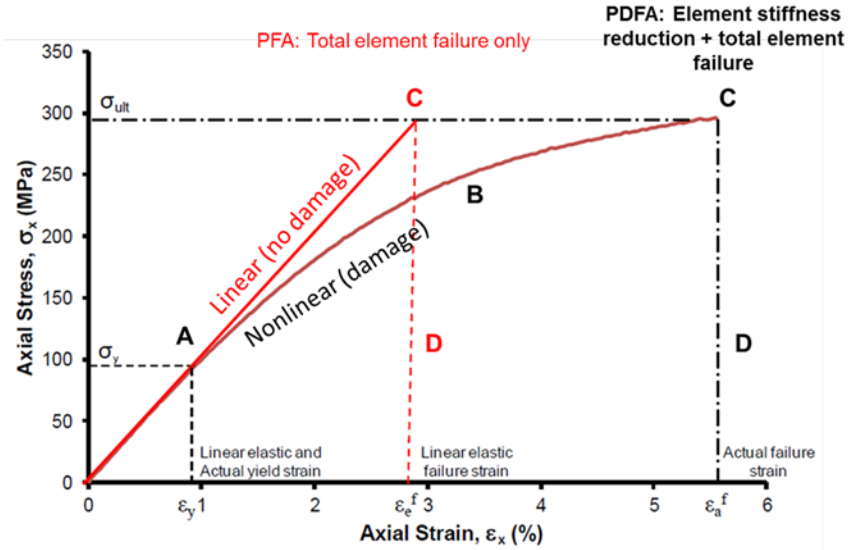

Figure 3. Schaefer model of material behavior

The general material model includes the following parts:

A. **Linear Response**: The linear response is the portion of the constitutive model in which proportional loading is valid, i.e., no matrix micro cracking.

B. **Pre-peak Response**: the pre-peak response is generally non-linear; however, the sophistication of the pre-peak model can differ greatly based on the formulation. For example, MAT162 has no inherent capability to handle material non-linearity. MAT261, on the other hand, employs tabular input data. The response can be entirely recoverable or only partially recoverable by setting the SIGY value in the material model. State-based peridynamics used in Phase I did not have ability to include non-linearity and to distinguish between recoverable and non-recoverable non-linearity. Additional improvements to state-based peridynamics as a result of the HEDI program are discussed in Cuenca et al. [12]

C. **Failure Criteria**: The failure criteria is generally determined based on the material form. Tape might have a different response than fabric or braids. This failure criteria tells the discretized domain when to fail.

D. **Post-Peak Response**: The post-peak response describes what happens in the discretized domain after failure. For MAT162, the post-peak response is calibrated softening of the element based on experimental data. MAT261 uses a fracture-based post-peak response in which a traction-separation law is added to the element response after failure. The total energy is normalized by the characteristic element length to ensure that the total energy released by the element is consistent with the input property in a mesh objective way. State-based peridynamics has an instantaneous release of energy based on a critical stretch criteria.

All of the selected methods, MAT162, MAT261, and state-based peridynamics (EMU PD), represent lamina level behavior. Both MAT162 and EMU PD also allow for potential scale-up to sublaminate modeling approaches in which the mechanics of multiple plies are considered in a single element/part [13]. The sublaminate approach involves developing appropriate failure mechanics at a length scale above the usual length scale of interest (e.g. lamina) but generally reduces the fidelity of the predicted damage. Since the solid element MAT261 is formulated specifically for tape based failure modes of interest, using a sublaminate modeling approach in MAT261 will violate the assumptions used for formulation. Computational efficiency could be improved through Near-Field Far Field modeling approach and/ or use of the shell formulation of MAT261 but requires further investigation. By isolating the portions of the material models (Table 2), developmental pathways can be developed for each of the methods.

Table 2. Material models as broken out by the Schaefer model components

Schaefer Model Region	LS-DYNA MAT162	LS-DYNA MAT261	EMU Peridynamics

A. Elastic Response	3D Elastic	3D Elastic	3D Elastic
B. Pre-Peak Response	None	Tabular non-linear shear data	None
C. Failure Criteria	Hashin/Matzenmiller	LaRC-04 [14]	Critical Stretch
D. Post-Peak Response	Softening Degradation	Energy Based Degradation	Instantaneous Degradation

LS-DYNA MAT162 is developed and licensed through The Material Sciences Corporation and is available for use with the LS-DYNA solver [15]. The material model will be evaluated on the program through the use of a sublaminate modeling approach. Due to the limitations of use with constant pressure elements, in order to better capture material behavior, it requires three elements through the thickness of a part. Using a ply-by-ply modeling approach is not feasible for large structures. As such, a sublaminate modeling approach is being explored. The McNair Center at The University of South Carolina is working on developing a nonlocal based user material implemented in LS-DYNA to address some of the shortcomings associated with use of native delamination versus tie-break contact features related to MAT162 [16] .

LS-DYNA MAT261 already has strain rate capabilities for Region B, the nonlinear shear, and Region C, the failure criteria. The MAT261 card allows for tabular data to be included as input properties for the in-plane strengths as a function of strain rate, and tabular input data for the nonlinear shear as a 3D table (e.g. strain rate vs. shear stress-strain). MAT261 is currently being assessed for inclusion of strain rate hardening capabilities for Region A, the elastic response. In the latest release of LS-DYNA, there is also an advanced tie-break contact feature that uses strain-rate dependent cohesive strengths. Together with the in-plane MAT261, a full strain-rate dependent description of the material model can be evaluated.

Boeing, NASA, and Sandia National Laboratory are working to develop a new capability in EMU PD to account for material nonlinearity and strain rate dependence. This improvement will enhance the predictive capability of the method.

A significant limitation of the material models as currently formulated is that underlying material form assumptions (e.g. tape, fabric, braid, woven, etc.) open limit the applicability of the material model for other material forms. While engineering approaches exist to calibrate the model for a different material form, the material model lacks the generality to be applicable for a broad range of material forms. With this limitation, NASA GRC in collaboration with Arizona State University, Ohio State University, George Mason University, FAA and LSTC has developed MAT213 [17]. MAT213 is a data driven tool that allows for the use of tabular data to populate a deformation model and damage model. The deformation model is based on the non-linear response of the material and is generated from monotonic loading. The damage model allows for reduction of stiffness along with coupling of the loss in other directions through hysteresis loading of coupons. The method material card can be developed from virtual testing to fill in the experimental gaps.

Verification of Material Models

For each of the selected methods, a verification pathway has been developed to establish the bounds over which a material model is applicable. Verification involves the comparison of simple models to known solutions and/or closed form calculations. The verification bounds the requirements for modeling the validation articles to capture the failure modes of interest that are predicted in the model. An example of a verification pathway for MAT261 is shown in Figure 4

MAT261 is characteristic of a continuum lamina-level fracture based PDFA tool containing the same A-B-C-D components as many other methods and is similar to the approaches that are examined by the NASA ACC Post-buckled stiffened panel with barely visible impact damage (BVID) [18] (e.g. CompDam and Enhanced Schapery Theory (EST)). As such, the benchmarks derived through the verification effort are applicable for MAT261 [19], [20]. MAT261 is an in-plane material model and does not include an inherent ability to account for delamination.

This requires the in-plane model to be coupled with LS-DYNA's native tie-break contact. The tie-break and MAT261 work together to complete the entire lamina-level material model.

In Figure 4, each verification cases contains three parts: (1) the name of the benchmark problem, (2) the region of the Schaefer framework being evaluated, and (3) the result of the verification case. The result could be the result of a lesson learned, a best practice, or a numerical calibration of the material model at the length scale of interest. An example of this would be the cohesive strength vs. mesh size curve used for the tie-break contact. These approaches are to be carried forward for subsequent modeling approaches.

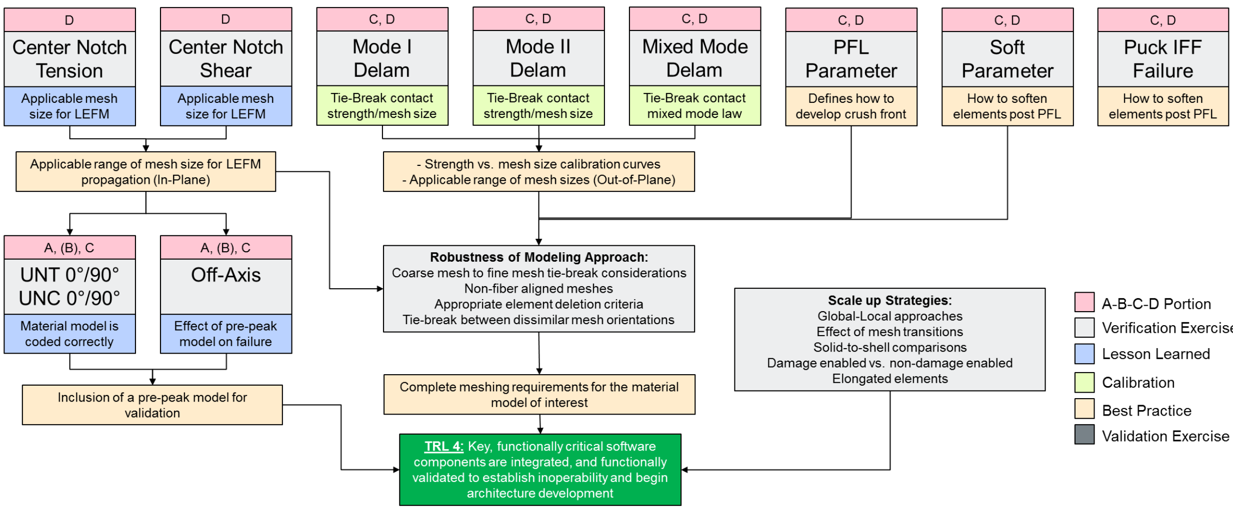

Figure 4. An example verification pathway for MAT261

The goal of each verification case for MAT261 is as follows:

- Center Notch Tension – Evaluate the ability of the code to propagate long opening cracks and establish applicable mesh sizes in which linear elastic fracture mechanics (LEFM) is applicable
- Center Notch Shear - Evaluate the ability of the code to propagate long sliding cracks and establish applicable mesh sizes in which LEFM is applicable
- Mode I Delamination – Generate the required cohesive strength versus element size for accurate calibration to test data for mode I delamination
- Mode II Delamination – Generate the required cohesive strength versus element size for accurate calibration to test data for mode II delamination
- Mixed Mode Delamination – This verifies that the tie-break contact parameters that have been developed for Mode I and Mode II are applicable for mixed mode delamination
- PFL Parameter – The PFL parameter is set to allow a crushfront to develop, once fully developed, it begins to soften elements around it by reducing the strength (for shells and thick shells only)
- Soft Parameter – The soft parameter works with PFL to reduce strengths of elements adjacent to the crushfront. This is a calibration parameter that can be determined from a test.
- UNT/UNC 0°/90° - Establish that the material model is correctly recovering strengths and stiffnesses
- Off-Axis – Establishes that failure envelopes are being accurately recovered. In this case, MAT261 uses the LaRC-04 failure criteria. CDM approaches in the past have shown difficulty recovering the failure criteria and has sometimes resulted in the election of not using the pre-peak model. This verification case helps identify if that is necessary.

Verification pathways for MAT162 and PD have also been developed following the same general framework in which damage modes at the length scale of interest are examined to establish best practices, proper numerical calibration, and provide lessons learned to carry forward to modeling strategies. These pathways will support model validation for impact problems by ensuring the proper lamina failure mechanics and interaction of damage modes (e.g. ply splits/cracks with delamination).

Impact problems, and in particular high energy impact problems, activate higher order failure modes that are difficult to replicate under quasi-static loading due to the inability to generate an energy flux that results in localization.

Each of the material models will be assessed for their applicability to HEDI events. The following outlines the technical approach for each method:

- MAT162 currently includes advanced failure criteria that includes localization effects including fiber crush and fiber tension-shear response. The model is calibrated to typical quasi-static punch shear test and depth of penetration data [21] to ensure applicability for HEDI.
- MAT 261 does not have the ability to account for explicit HEDI failure modes associated with failure mechanics such as fiber crush and fiber tension-shear. In recent work a ‘hot fix’ has been developed to allow for element stability via matrix residual strength after failure [22].
- PD has the implicit assumption that these failure modes can be captured providing that the discretization of the space is appropriate. Since the failure criteria of the fiber direction bonds is based on a critical stretch, the contribution of shear and tension is inherent to the formulation.

Development of Modeling Strategies

High fidelity PDFA predicts damage at the ply-level; however, this level of detail may be prohibitive when examining large structures. Performing ply-by-ply modeling approaches with fracture based continuum lamina level PDFA approaches with tie-break contact requires significant discretization that results in a large number of elements. For example, the maximum allowable element size for verification of MAT261 is approximately 0.010” to accurately capture matrix cracking failure modes. For a 24” x 24” flat panel validation, this results in approximately 5.76M elements per ply if the entire panel were to be discretized. For 24 to 48 plies, this would result in 138M elements and 276M elements, respectively. Even at the flat panel level, this is likely not feasible. For this reason, it is necessary to develop modeling strategies.

Modeling strategies will be developed and defined based on a program definition of a tractable limit. A tractable limit is required to be set to be characteristic of a time and computational resource requirement that is representative of capabilities of an aerospace original equipment manufacturer. This limit for example could be that the simulation must complete in under two (2) weeks using no more than 300 CPUs. Methods will be used with best practices defined from verification until the tractable limit is reached, at which point, modeling strategies will be developed.

Preliminary modeling strategies for each of the methods are as follows:

- LS-DYNA MAT162
    - Since MAT162 does not involve fracture considerations, there are no limitations to discretization that affect scale-up. Best practices require three (3) elements through the thickness of a ply to better capture bending responses; however, this may not be tractable from the beginning. A ply-by-ply modeling approach is used in pre-test prediction in which each ply has one element through the thickness and tie-break contact. This approach limits predictive capability as it interacts with the native delamination capability of MAT162 and the elements are generally not stable. A sublaminate modeling approach is being explored to address these issues. Like EM PD, the predicted damage states will be decoupled from the ply mechanics, but will have a reasonable estimation of general damage morphologies and energy considerations.
- LS-DYNA MAT261
    - Below Tractable Limit: Ply-by-ply modeling with fiber aligned meshing [23] will be utilized using a single element through the thickness of a ply. The in-plane material response will be governed by MAT261 with the out-of-plane response being governed by tie-break contact. The models will utilize a Near Field, Far Field (i.e., global-local) co-model approach in which a region of fine mesh will be embedded in a model with a coarse mesh. As a best practice, the damage area will be five times (5x) the diameter of the impactor to ensure damage can spread.
    - Above Tractable Limit: The matrix failure modes may be neglected to allow for large elements sizes but still recover the energy associated with fiber breakage. In order to use this approach, quantification of error will be iterated at the flat panel level.
- EMU PD
    - Below Tractable Limit: Ply-by-ply modeling will be utilized using a single material point through the thickness of a ply. Uniform grid spacing will also be used. Bonds will be prescribed for the fiber direction and matrix direction with matrix direction bonds defining the through thickness response as well as transverse response.
    - Above Tractable Limit: A sublaminate modeling approach will be utilized using a single material point to represent multiple plies to be defined by the model. At this point, the bonds no longer

represent physical damage modes and lose relevance to the length scale of interest. Damage cannot be correlated with discrete damage events from the simulation; however, general damage morphologies and energy absorption can be considered.

Validation of Material Models

The material models will be validated through a detailed experimental program that follows a building block approach. Factors that generally limit the ability of validate advanced material models such as boundary conditions, contact conditions, and impactor response have been previously validated and will reduce uncertainty in the validation approach. The building block is shown in Figure 5.

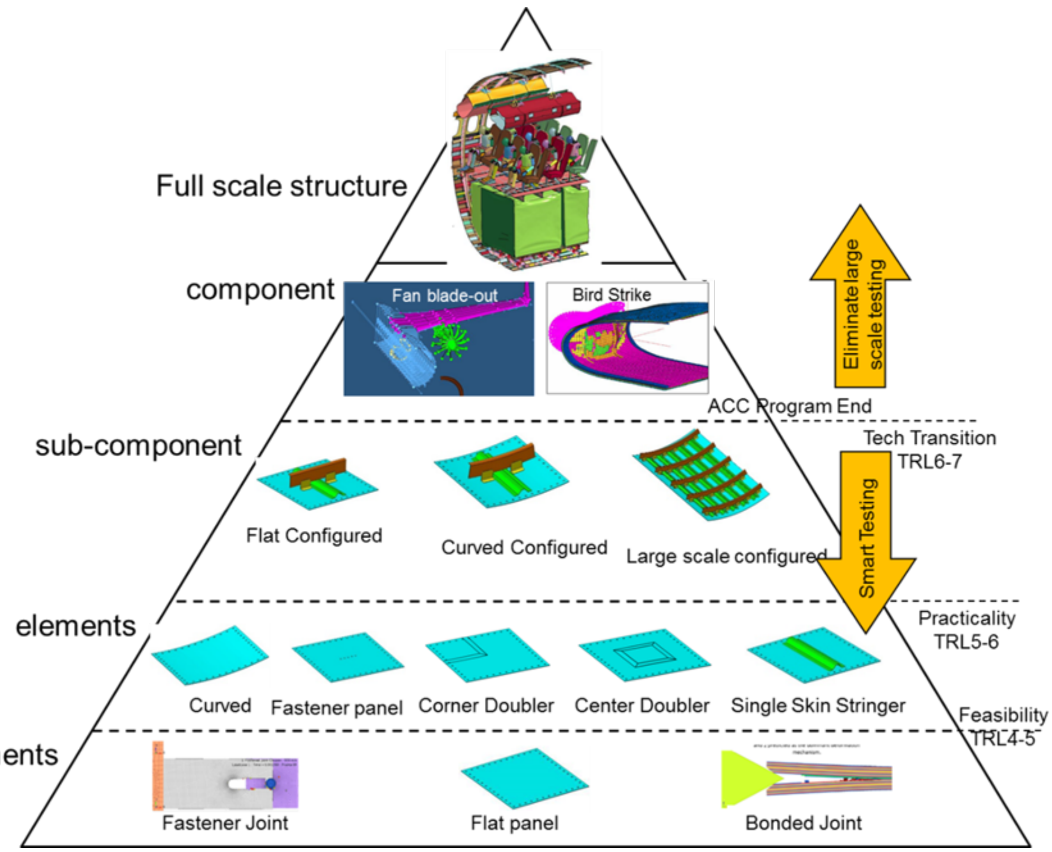

Figure 5. HEDI Building block approach

The bottom of the building block contains three major features of the elements and sub-components tested in the program. These features are as follows:

1. A twenty-four (24) ply quasi-isotropic lay-up flat panel. The flat panel provides a good baseline for comparison with the Phase I effort while addressing the short comings of the flexane impactor. This flat panel is representative of the skin that will be used on test articles further up the building block. The test article will be subjected to HEDI loading to determine the ballistic limit.
2. A bolted joint to better understand the behavior of substructure attached to the test articles (e.g. a mechanically fastened shear tie to a skin)
3. A bonded joint to better understand the disbond behavior under mode I and mode II loading. This will help better inform the requirements for test articles that include a cobonded stringer. An example of this work is presented previously in the work of Ravindran et al. [24].

The next level of the building block includes the combination of the aforementioned features. These test articles include the following:

1. A curved panel: A skin that is identical in lay-up to the flat panel includes curvature of a finite radius. This article will be used to help understand the contact considerations of an impactor striking a deforming material with a radius.
2. Flat panel with fasteners: A skin with seven (7) fasteners in a row are used to replicate the results of joined sections. The article will be used to examine how the fasteners arrest damage during HEDI.
3. Flat panel with a doubler: An interleaved doubler is placed either in the middle or corner of the panel and impacted at the panel center. The article will be used to examine how far the doubler needs to be extended past a threat zone and how effective is the ramp at dissipating the energy.
4. Skin-stringer: A hat stringer is cobonded to the skin and subjected to impact loading of the outer mold line (OML). The article will be used to examine how a cobonded stringer flange may disbond under impact loading.

The building block then adds complexity at the next level in which curved geometry, stringers, frames, and shear ties are considered to build a structure. The final test article is a fully configured panel that includes five (5) stringers and five (5) frames. Ballistic limits will be determined for all of the test articles.

High fidelity validation data will be developed as part of the test plans including the parameters to identify for test-analysis correlation. High speed photogrammetric techniques and 3D digital image correlation (DIC) will be recorded during the impacts. Boundary conditions were previously verified in Phase I using four (4) load cells placed around the frame. This data will be used to assess the global model response. Test articles of interest will be subjected to further non-destructive and destructive evaluation. Samples will be ultrasonically scanned and imaged with computed tomography (CT) to determine the ply-by-ply damage states.

At each building block stage, simulation with the selected methods will be used to inform design details (including holding fixtures) and set the impact energy range. Early and ongoing use of simulation helps to reduces testing cost and ensure relevance to in-service experience.

Assessment of Tech Gaps

The CRT has worked to develop an objective set of success criteria for overall test impact program to enable degree of goodness for test-analysis correlation and material model comparison. From the validation, tech gaps will be assessed through the development of the HEDI ‘Playbook’. The HEDI Playbook (see Figure 6) will be used to quickly identify what material model is applicable for predictive capability across length scales by either using the model as originally intended, or developing scale-up strategies such as the MAT162 or PD sublaminate modeling approach, or hybrid of methods. The Playbook will allow future analysts to quickly assess what tool is recommended for a problem, and the degree of maturation via TRLs, whether to use the standard or scale-up strategies, and finally, what is a reasonable expectation for success. The Playbook will also serve as an opportunity to address the tech gaps in the future beyond the completion of the ACC Phase II program.

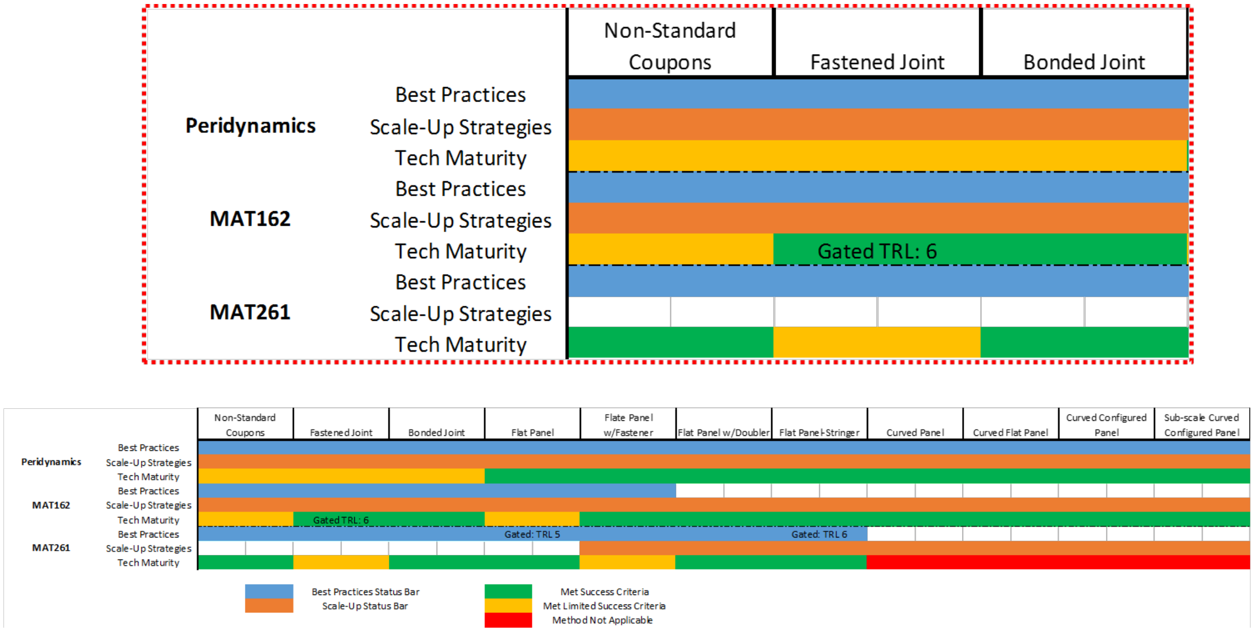

Figure 6. Notional HEDI 'Playbook'

III. Preliminary Results

In year two (of three) of the ACC HEDI Phase II program, the CRT has worked to close a number of tech gaps associated with Phase I efforts. These efforts include the following:

1. Development of objective validation success criteria
2. Development of a validated projectile to reduce uncertainty associated with the impact
3. Development of a verification pathway for both MAT162 and MAT261
4. Perform updated testing on flat panels in addition to panels with fasteners and doublers, stringer and curved panel
5. Perform elevated loading rate testing of bolted and bonded joints
6. Perform pre-test predictions to help guide initial model development and test configurations

Development of Objective Success Criteria

Validation of advanced PDFA models is non-trivial and requires careful consideration in terms of the length scale at which damage is predicted, the available inspection data, how the material model is formulated, and the end application of the tool. With all of these factors considered the CRT worked to develop preliminary objective success criteria, Figure 7. The success criteria for impact event simulation has been developed in consideration of the Schaefer method framework to better identify which part of the material model might be affecting predictive capability. Success criteria is generalized for HEDI following the CMH-17 Crashworthiness criteria [25] and falls in to one of four categories based on error from the as measured state:

1. Excellent Agreement – The absolute error in the model is less than 10% for the metric of interest
2. Good Agreement – The absolute error is greater than 10% but less than 19% for the metric of interest
3. Fair Agreement – The absolute error is greater than 20% but less than 29% for the metric of interest
4. Poor Agreement – The absolute error is greater than 30%

The simulation response is broken in to the global response and the local response. The global response experimental data will be generated in-situ during testing from the load cells and the high speed photogrammetry. The local response will refer to the ply-by-ply damage that develops as a result of the impact and will be generated after testing via non-destructive evaluation (NDE). From the global response, the first two metrics of comparison are the panel peak deflection and panel force response. The panel reaction force will consider the average and peak response from force-time history. For the force-time history, the shape of the response will be considered using a Sprague and Geers method [26], [27]. The other success criteria for the global response will be the panel threshold velocity (also called ballistic limit or V50). These measurements when compared to simulations evaluate the ability of the material to dissipate energy through a variety of failure modes.

The local response will be compared to the model by examining the high fidelity post-test inspection data. Time-of-flight ultrasonic scanning will be used to give a generic damage state through the thickness of a sample in addition to ultrasonic amplitude. These NDE measurements will be used to determine total area of the material removed as a result of the impact as well as the extent of damage. When required, CT images will be used to determine the ply-by-ply delamination and damage modes. While the damage modes will be part of a qualitative assessment, the delamination provides a quantitative basis for evaluation of the material models.

Success criteria has also been developed for the bolted joint and bonded joint validation articles. The metrics proposed in Figure 7 are applicable for the impacts regardless of size of the structure. For larger test articles, the success criteria may need to be applied on the local level to account for discrepancies that might exist between the fidelity of the models due to modeling limitations and experimentally generated data.

	Comparison	Metric	Excellent	Good	Fair	Poor
Global Response	Panel Deflection Response	Deflection-Time History [1] (A-B)	< 10%	10-19%	20-29%	> 30%
	Panel Force Response	Force Time History[1] (A-B-C-D)	< 10%	10-19%	20-29%	> 30%
		Peak Force (A-B-C-D)	< 10%	10-19%	20-29%	> 30%
	Panel Threshold Velocity	V50[2] (A-B-C-D)	< 10%	10-19%	20-29%	> 30%
Local Response	Laminate Damage Size	Projected Through Thickness Damage[4] (D)	< 10%	10-19%	20-29%	> 30%
	Ply-by-Ply Damage	Area of Damage[3] (D)	< 10%	10-19%	20-29%	> 30%
	Modes of Failure	Delamination, Fiber Breakage, Matrix Cracking	< 10%	10-19%	20-29%	> 30

[1] Sprague and Geers' method
[2] Average of lowest speed penetration and highest speed rebound
[3] Ply-by-ply level damage pattern and area at regions of interest using damage mapping for pre-selected cases for NDE (case-by-case, CT scan and/or destructive evaluation)
[4] Laminate level extent of damage area at regions of interest for pre-selected cases for NDE (ultrasonic amplitude and time of flight)

$$Relative\ Error = \frac{|Simulation - Experiment|}{Experiment} * 100\%$$

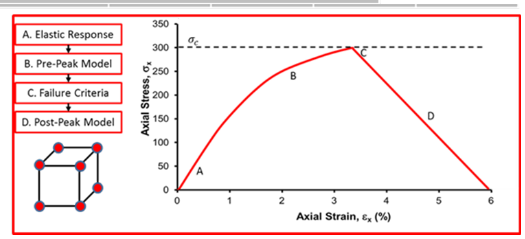

Figure 7. Preliminary success criteria developed by the team

Development of Validated Phase II Projectile

Modeling of the Phase I flexane projectiles (blunt and sharp) proved too difficult in order to validate the panel modeling approaches. To correct this technical gap, the CRT elected to update the projectile. Following the ASTM Standard D8101 [28] as a baseline, a hollow cylindrical shape of 2" diameter with semi-spherical end geometry was updated to include more mass in the front of the projectile to achieve higher impact energies. The projectile is machined from Aluminum 6061-T6 and has been shown to be strain-rate dependent. Using the work of Manes et al. [29] a LS-DYNA MAT_098 card had been developed for the material.

To validate the material card, a projectile was fabricated by Boeing and shot at a rigid steel plate by NASA GRC. The projectile was shot at a speed of 605 ft/s, above the impact velocities performed in Phase I. The projectile's speed and deformation were analyzed using digital image correlation (DIC). At the completion of the test, the sample had accumulated a significant amount of plastic deformation. The deformation was measured using a coordinate measure machine (CMM) and a 3D rendering of the final deformed shape was generated.

The projectile was modeled using the MAT_098 material card which employs simplified Johnson-Cook strain sensitive plasticity by ignoring thermal effects and damage. The projectile model was meshed with 0.05” solid hex elements to provide good contact between the projectile and the impacted panel surface. Hourglass control type 6, Belytschko-Bindeman was selected. A comparison of the undeformed projectile model to the deformed simulation and test projectile is shown in Figure 8.

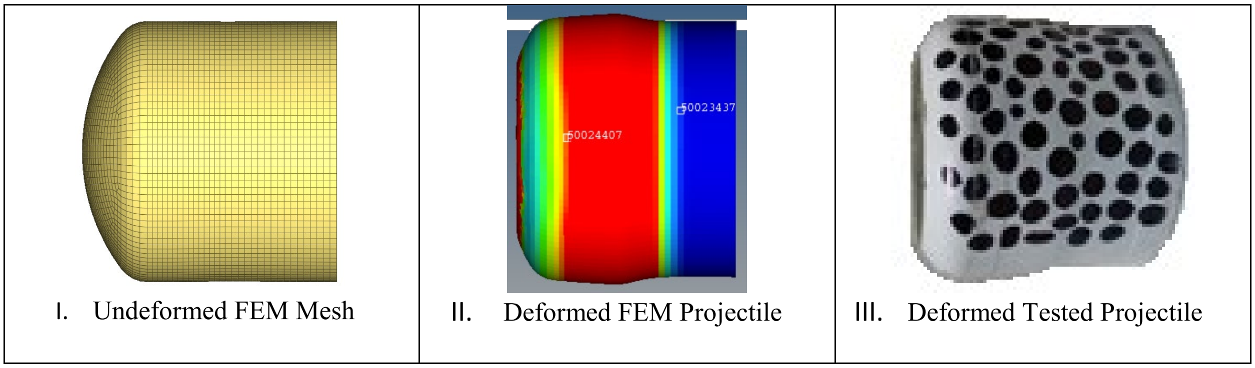

Figure 8. Comparison of undeformed simulation to deformed and tested projectile

Figure 9 shows an overlay of the deformed geometry of the as measured CMM and the LS-DYNA simulation shot at 605 ft/s. The deformed projectiles between the simulation and test agree within 10%. As a result, when combined with the boundary conditions analysis performed in Phase I, the validated projectile and boundary conditions eliminate much of the uncertainty associated with modeling the HEDI events being tested in the building block approach. This further allows for objective evaluation of the methods and modeling approaches used in Phase II.

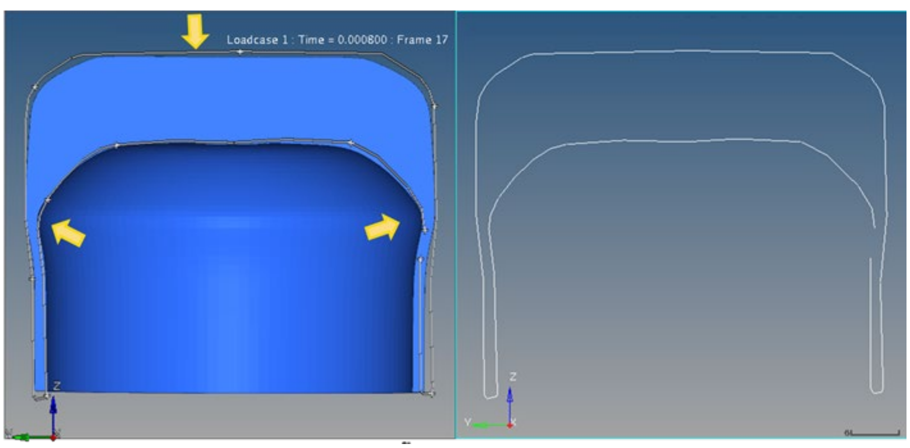

Figure 9. Comparison of deformed damage state of the test projectile as measured by CMM to the LS-DYNA simulations at 605 ft/s

IV. Summary

An objective approach for developing, verifying, and validating analysis tools and methods to predict performance of safety-critical engine and airframe structures dominated by high-energy impact events under the NASA ACC has been presented. The approach has been built to close technical gaps observed in Phase I and provide a building block-like validation plan to assess the predictive capabilities. The Phase II work of the CRT seeks to continue towards the goal of developing tools to pursue smarter testing and reduce number of required tests for advanced composite structures prior to certification on future aircraft development programs.

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