RUNWAY DEBRIS IMPACT ON GENERIC COMPOSITE TURBOFAN BLADE MULTISCALE PROGRESSIVE FAILURE ANALYSIS

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ABSTRACT

The use of composites in turbofan engine structures requires an accurate assessment of damage tolerance such as bird-strike, hail impact, tool drop. Relying on test alone to evaluate such damage is costly, time consuming, and can delay entry of engine into market. Test validated advanced computational multi-scale and multi-physics damage tolerance approach is proposed to evaluate the damage process. The approach is effective at various levels of the building block of structures for a fan blade. The analytical approach was first validated with test data for laminate. Then it was applied to the evaluation of generic turbofan blade impact. The results for blade impact indicated that initially the low energy impact could only make minor damage but mainly made of fiber damage. Delamination was found when impact energy increased to 10J. Furthermore higher energy impacts were modeled and evaluate delamination propagation pattern.Details are discussed next.

1 Introduction

Polymer composites have found many applications as advanced engineering materials due to their lightweight, relative low cost, and the evolution of automated composite material/structure fabrication processes. These materials are now essentially employed in turbofan engine structures. This trend is intensifying with the development of: new constituent materials, fiber reinforcement configurations with superior mechanical properties, and improved manufacturing processes. With all these advancements, Damage tolerance analysis, especially impact, are inadvertently block relative components into service. Table 1 shows typical projectile source encountered in service of turbofan engine.

FAA describes the categories of damage & defect considerations for primary composite aircraft structures [1]. These categories comply with FAA certification requirement as a part in service under allowable defects or repair scenario:

Category 1: Damage that may go undetected by field inspection methods

Category 2: Damage detected by field inspection methods specified intervals

Category 3: Obvious damage detected within a few flights by operations focal

Category 4: Discrete source damage known by pilot to limit flight maneuvers

Category 5: Severe damage created by anomalous ground or flight events

Description	Energy (J)	Mass (g)	Velocity (m/s)	Circumstances
Tool drop	6	330	6+	Maintenance work
Hail (up to 51mm diam.)	43	62	37.3	Take-off, landing, flight and taxiing
Bird strike	3.8-81kJ	1800	65-300	Take-off and landing, flight
Runway debris	2-40	9	20-94	Take-off, landing, flight and taxiing
Concentrated load	50	-	Static	Maintenance, cargo handling

Table 1 Common type of projectile impact on aircraft

Relying on test solely to evaluate such effects is costly, time consuming, and can delay engine certification and entry into market. To mitigate risk associated with potential impact damage in-service, the authors evaluated the benefits resulting from the application of advanced multi-scale/ multi-physics durability and damage tolerance approach to reduce testing and accelerate certification of composite fan blade. The analytical approach combined micromechanics with finite element analysis, damage tracking and fracture, and lamina property prediction. Figure 1 shows an example of runway debris and FOD system [2].

Figure 1 Runway debris and FOD detective system

The work presented in this paper evaluated impact damage from multiple energy on generic composite turbofan blade. This provided a framework for test guidance and designing a test article capable of showing the real effects of foreign object impact as it may take place during operations. The main objective of the work presented here is to evaluate the feasibility of using a robust computational approach to evaluate the debris impact as encountered to engine blade. Four level of energy were modeled and their effects evaluated: damage and initial delamination. The work is motivated by the desire to reduce testing during the certification of the turbofan engine.

2 Description of Analysis Approach

2.1 Modeling of Multi-scale / Multi-function Laminate Composite

The multi-factors [3] that influence a metered behavior are represented by a multifactor interaction model of multiplicative form where each factor is expressed in expanded form, as shown in Figure 2. The exponents are selected so that they satisfy the initial and final conditions. The exponent can have any value which describes the factor behavior from its initial value to its final value as shown. There are two restrictions in selecting exponents: One is that they only can take positive values and the second is that the factor within the parenthesis must have absolute value. The material degradation behavior of both the metallic structures and the composite aircraft component structure are characterized by the multi-factor interaction model.

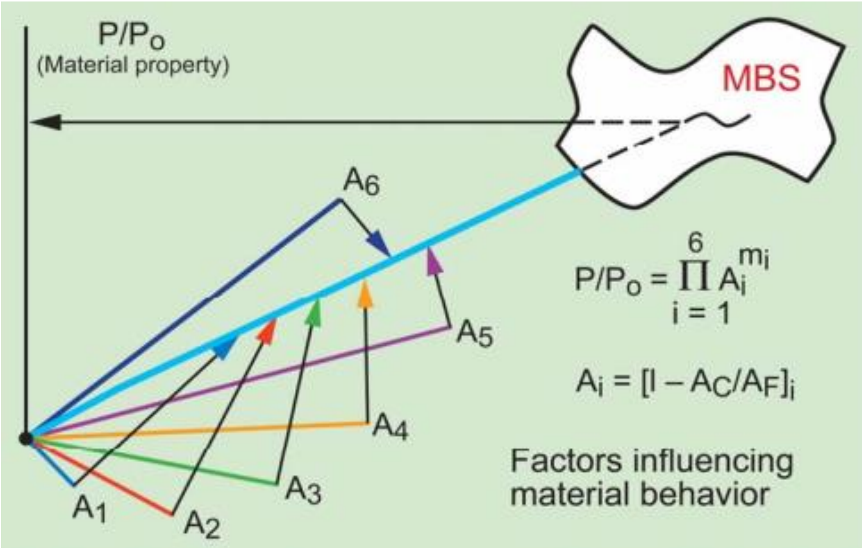


Figure 2 Multifactor interaction model with subtracting

Micromechanics based optimization subroutine, Figure 3, is used to reverse engineer complete transversely anisotropic fiber and isotropic or anisotropic matrix behavior with in-situ nonlinearity effects, Poisson's ratio, and strength properties using in-plane test data [4]. The input to the optimization subroutine is in-plane ply properties, vendor fiber tension modulus, vendor reported fiber volume ratio, matrix modulus and void volume fraction. The results are in-situ constituent material properties because they account for thermal residual stresses due to curing, environmental effects (temperature, moisture, etc.) and fiber-matrix interface. MCQ is for un-notched laminates and once the study of material systems is satisfactory users move to MS-PFA which uses FEA coupled with MCQ to study any other geometrically complex system from coupon to full scale structures.

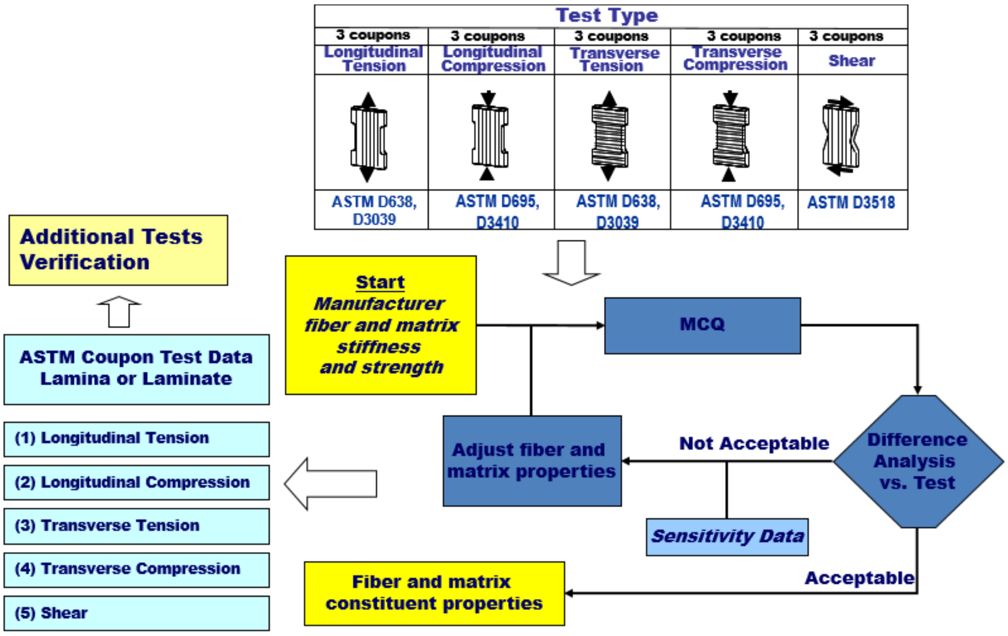


Figure 3 Procedure of material calibration and characterization

2.2 Description of Multi-scale Progressive Failure Analysis

The Progressive Failure Analysis software “GENOA” augments finite element software by providing progressive failure analysis based on damage tracking and material property degradation at the micro-scale of fiber and matrix, where damage and delamination have their source. GENOA uses micro and macro interaction method in the composite structural progressive failure analysis procedures.

Figure 4 shows a flow chart and the micro-macro interactions that help the software investigate structural responses to composite material degradation from damage induced by loading and environment. Failure is properly assessed at the fiber, matrix or interface scale. Thus the methodology augments FEA analysis, with a full-hierarchical modeling that goes down to the micro-scale of sub-divided unit cells composed of fiber bundles and their surrounding matrix. The damage tracking is decomposed from global structural level to micro-scale level. The stresses and strain at micro level are calculated using a mechanics-of-material-approach from the finite element analysis results of the macro-mechanical analysis at each load increment [5]. Displacements, stresses, and strains derived from the structural scale FEA solution at a node or element of the finite element model are passed to the laminate and lamina scales using laminate theory. Stresses and strains at the micro-scale are derived from the lamina scale stresses using micro-stress theory. The latter are interrogated for damage using a set of failure criteria.

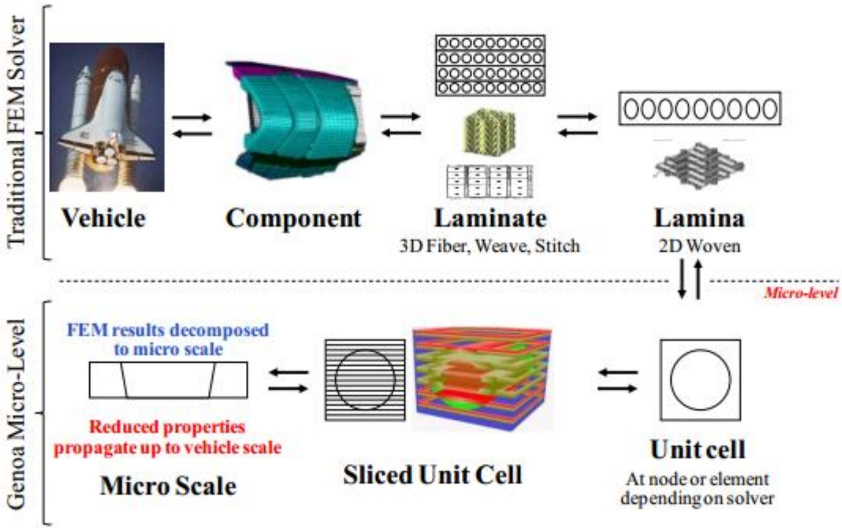


Figure 4 Multi-scale progressive failure analysis procedure

This procedure enable the analysis of damage initiation and progression including fracture initiation on a micro (fiber/matrix) level. The damage mechanisms account for matrix cracking under transverse, compressive, and shear loading. The ply fracture mechanisms include fiber failure under tension, compression (crushing, micro-buckling and de-bond), and delamination. It allows: (1) use of commercial finite element stress solvers; (2) automatic update of the finite element model prior to executing FEA stress solver for accurate lamina and laminate properties; and (3) degradation of material properties at increase loading based on detected damage.

3 Results and Discussion

3.1 Material Characterization

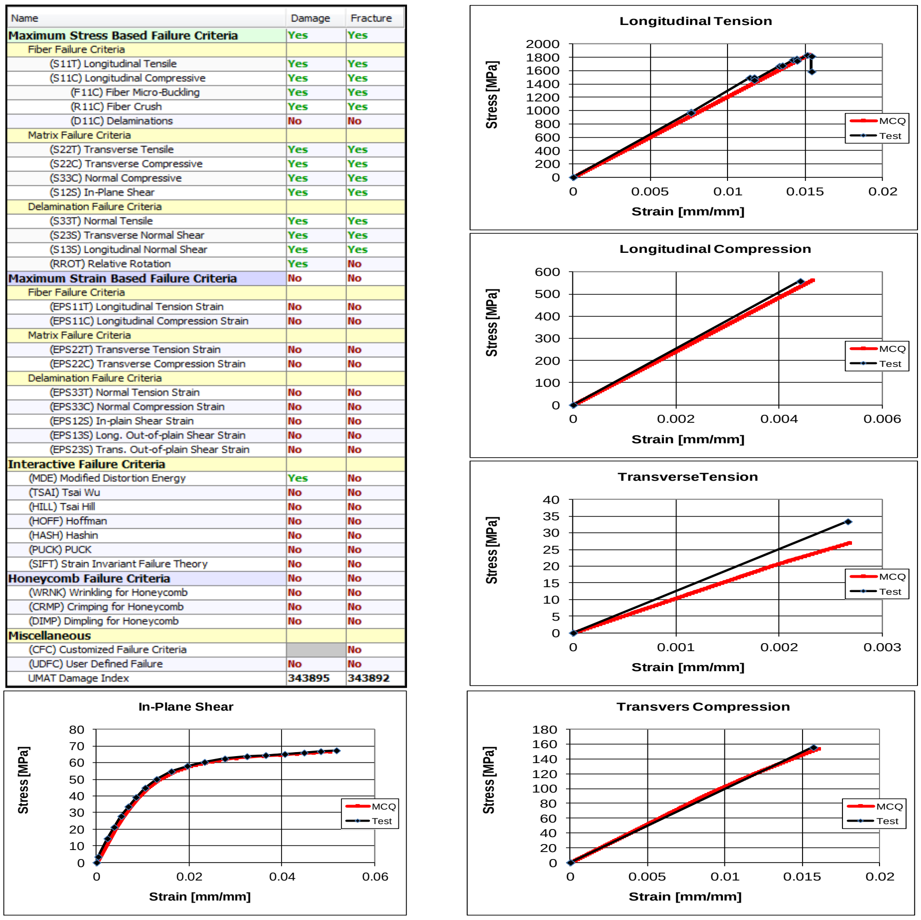
In the article, carbon/epoxy system is calibrated using material from GENOA database from previous project and 5 ASTM test performed to obtain necessary data for material modeling. Table 2 shows engineering reversed constituent property.

Matrix effective property		
Symbol	Effective	Units
E_m	3.73	[Gpa]
ν_m	0.36	
S_mT	52.54	[Mpa]
S_mC	244.97	[Mpa]
S_mS	107.51	[Mpa]
Fiber effective property		
Symbol	Effective	Units
E_{f11}	207.485	[Gpa]

E_{f22}	24.078	[Gpa]
ν_{f12}	0.302	
ν_{f23}	0.480	
G_{f12}	35.113	[Gpa]
G_{f23}	8.136	[Gpa]
$S_{f11}T$	3121.20	[Mpa]
$S_{f11}C$	794.99	[Mpa]

Table 2 Effective fiber/matrix property

As observed in Figure 5, good agreement between test and simulation is achieved through the calibration process.



Name	Damage	Fracture
Maximum Stress Based Failure Criteria	Yes	Yes
Fiber Failure Criteria		
(S11T) Longitudinal Tensile	Yes	Yes
(S11C) Longitudinal Compressive	Yes	Yes
(F11C) Fiber Micro-Buckling	Yes	Yes
(R11C) Fiber Crush	Yes	Yes
(D11C) Delaminations	No	No
Matrix Failure Criteria		
(S22T) Transverse Tensile	Yes	Yes
(S22C) Transverse Compressive	Yes	Yes
(S33C) Normal Compressive	Yes	Yes
(S12S) In-Plane Shear	Yes	Yes
Delamination Failure Criteria		
(S33T) Normal Tensile	Yes	Yes
(S23S) Transverse Normal Shear	Yes	Yes
(S13S) Longitudinal Normal Shear	Yes	Yes
(RROT) Relative Rotation	Yes	No
Maximum Strain Based Failure Criteria	No	No
Fiber Failure Criteria		
(EPS11T) Longitudinal Tension Strain	No	No
(EPS11C) Longitudinal Compression Strain	No	No
Matrix Failure Criteria		
(EPS22T) Transverse Tension Strain	No	No
(EPS22C) Transverse Compression Strain	No	No
Delamination Failure Criteria		
(EPS33T) Normal Tension Strain	No	No
(EPS33C) Normal Compression Strain	No	No
(EPS12S) In-plain Shear Strain	No	No
(EPS13S) Long. Out-of-plain Shear Strain	No	No
(EPS23S) Trans. Out-of-plain Shear Strain	No	No
Interactive Failure Criteria		
(MDE) Modified Distortion Energy	Yes	No
(TSAI) Tsai Wu	No	No
(HILL) Tsai Hill	No	No
(HOFF) Hoffman	No	No
(HASH) Hashin	No	No
(PUCK) PUCK	No	No
(SIFT) Strain Invariant Failure Theory	No	No
Honeycomb Failure Criteria	No	No
(WRNK) Wrinkling for Honeycomb	No	No
(CRMP) Crimping for Honeycomb	No	No
(DIMP) Dimpling for Honeycomb	No	No
Miscellaneous		
(CFC) Customized Failure Criteria		No
(UDFC) User Defined Failure	No	No
UMAT Damage Index	343895	343892

Figure 5 Stress-strain curve of AS4-3501

A summary of material calibration results for the materials is shown in Table 3. The table shows the test and MCQ properties and differences. Some experimental stiffness and strengths were provided and the rest of the properties were assumed based on literature. Fiber Volume Ratio and Void Volume Ratio were set to 57.06% and 2.03%, respectively. Matrix $S_{22}T$ was changed from 33.436 to 27.07 in order to account for correlation ($S_m T$ reduction).

Fiber/Matrix FVR=59.06%, VVR=2.03%				
Property	Test	MCQ	% Error	Units
E_{11}	121.469	121.54	0.06	[Gpa]
E_{22}	10.446	10.45	0.00	[Gpa]
E_{33}		10.45		[Gpa]
G_{12}	5.109	5.11	0.00	[Gpa]
G_{13}		2.65		[Gpa]
G_{23}		5.11		[Gpa]
ν_{12}	0.32496	0.32	0.00	
ν_{13}			0.32	
ν_{23}			0.55	
$S_{11}T$	1826.93	1845.20	1.00	[Mpa]
$S_{11}C$	558.218	563.20	1.00	[Mpa]
$S_{22}T$	33.436	27.07	-19.05	[Mpa]
$S_{22}C$	155.895	154.23	-1.07	[Mpa]
$S_{33}T$		33.41		[Mpa]
$S_{33}C$		155.79		[Mpa]
$S_{12}S(5\%)$	66.714	66.72	0.00	[Mpa]
$S_{13}S$		66.71515		[Mpa]
$S_{23}S$		57.02261		[Mpa]

Table 3 Summary of material calibration

3.2 Prediction of Debris Impact on Turbofan Blade

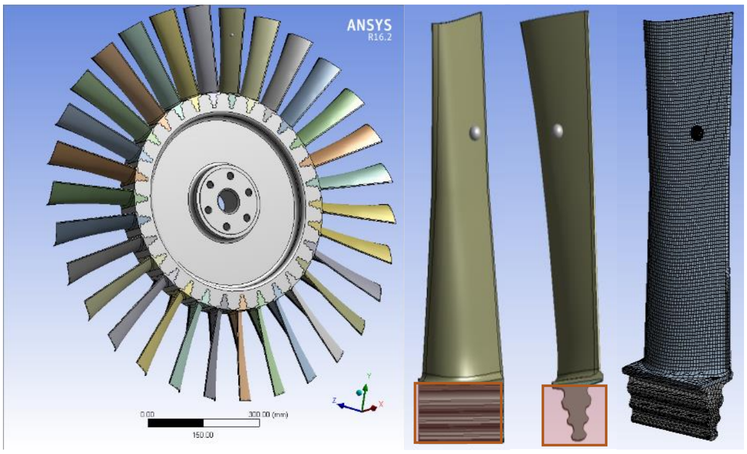


Figure 6 Fan blade FEM model

The model was created using pre-processor software (ANSYS workbench). Debris is modeled as spherical rigid body, 9 gram, out of steel solid elements used no damage is assumed to happen. Four different velocities (21m/s, 47m/s, 66.7m/s and 94m/s) were set to predict damage propagation. Blade is clamped at the bottom simulating connection the rotor. Blade is modeled using quasi-isotropic CFRP laminate previously calibrated using MCQ-Composites. 44534 solid elements are used in total for blade. The entire tools used in the simulation is shown Table 4.

MCQ-Composites 6.4	GENOA 6.4	ANSYS workbench 16.3	LS-Dyna pre-post 4.7	LS-Dyna 8.10
Multi-scale material modeling	Post processing	Pre processing	Post processing	Solver
Including Non-linearity	damage evaluation and Prediction	FEM modeling	stress and strain evaluation	GENOA UMAT implemented

Table 4 Tools used in simulation

Figure 7 indicates that matrix failure dominated over all failure while fiber failure occurred. It shows the matrix damage grows rapidly with impact energy increase. Nearly 70% of the damage was caused by matrix in 40J impact. Longitudinal Compression (S11C) damage represented the fiber was failing as well due to micro-buckling or fiber-crushing. Failure due to Longitudinal Tension (S11T) is observed in a less quantified way (Maximum 3.219%) but is still present, especially around the impact region. Diffuse damage shape was observed to propagate through the thickness as well. Generally impact force increase contact force between blade and debris.

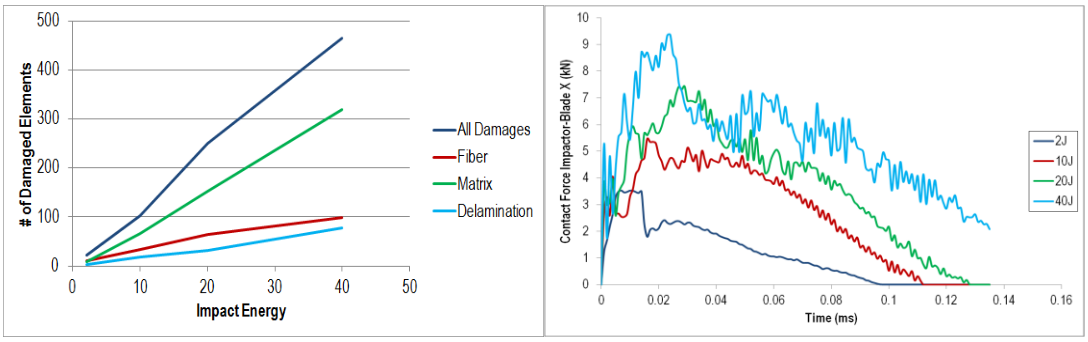


Figure 7 Damage evolution and contact force

It was found that damage pattern varied significantly with the different debris impact energy. Figure 8 shows no damage at the backside of the impact location, no significant structural damage was observed while impact energy was 2J. At 10J impact energy, matrix failure propagate through the width of the blade. Matrix failure starts to propagate inside the structure but not completely through the thickness while delamination occurs. Barely visible damage (BVID) is expected at this impact energy level. When impact energy increases to 20J, matrix damage propagates through width and thickness, reach the backside of impact location. Delamination spreads from impact location. The damage propagates in special 45° direction. Finally 40J impact energy makes the matrix damage reaches the edge of the blade and visible damage expected at the backside of the structure.

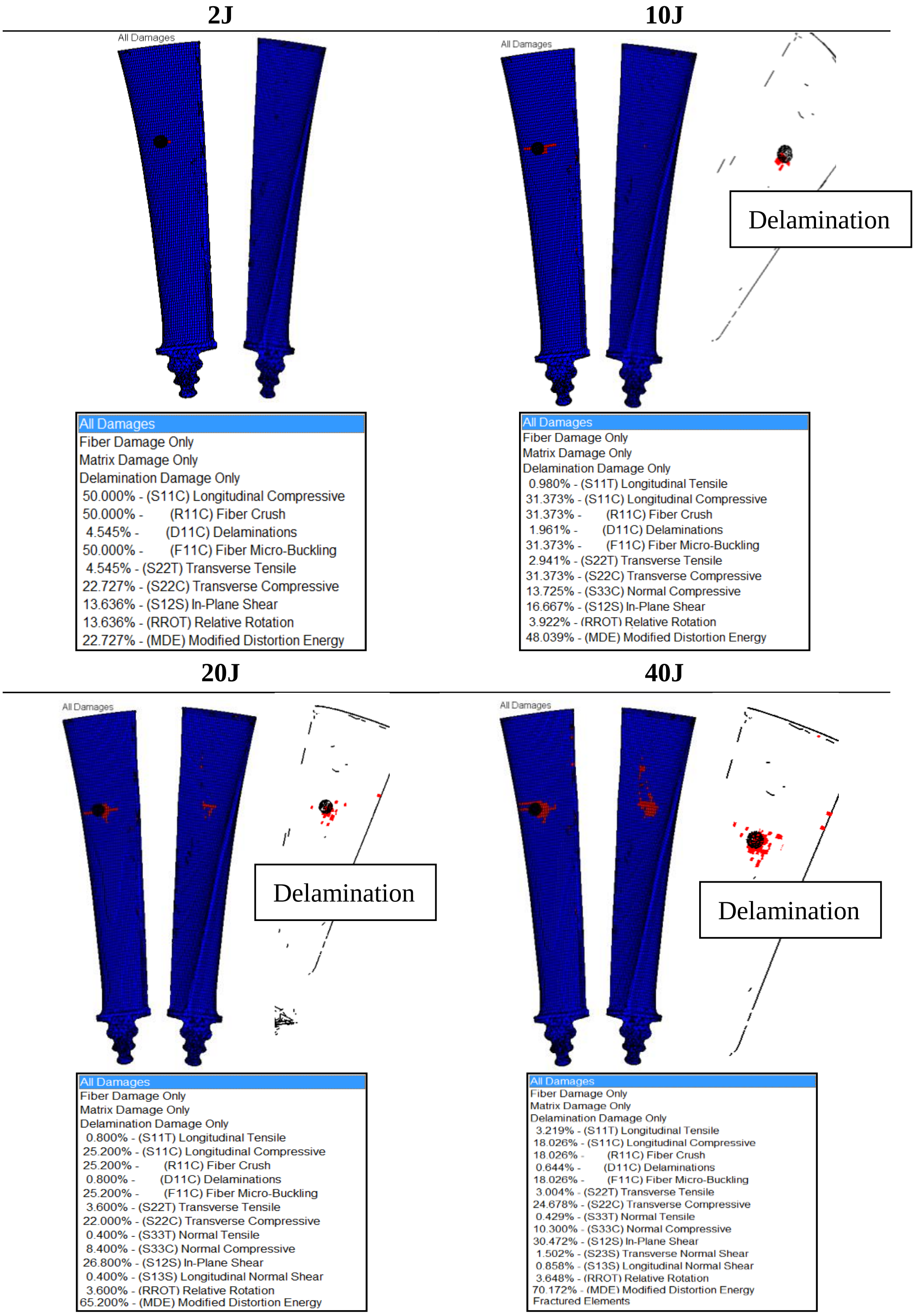


Figure 8 Damage evolution

Damage propagation detail at 20J was generated by GENOA and shown in Figure 9, where red area represent the damaged blade part. The simulation predicted damage mechanisms (S11T, S22T, S11C, S22C and S12S) are computed as a percentage over the total number of damaged elements. As it can be observed, after the contact force peak the amount of compression damage modes (S11C and S22C) stay more or less constant through the simulation while tension damage modes and in-plane shear (S11T, S22T, S12S) increase respect to peak point. Percentage of tension and shear modes grow while a sudden occur of S11T is observed at T2 point. Tension damage may be trigged due to centrifugal force.

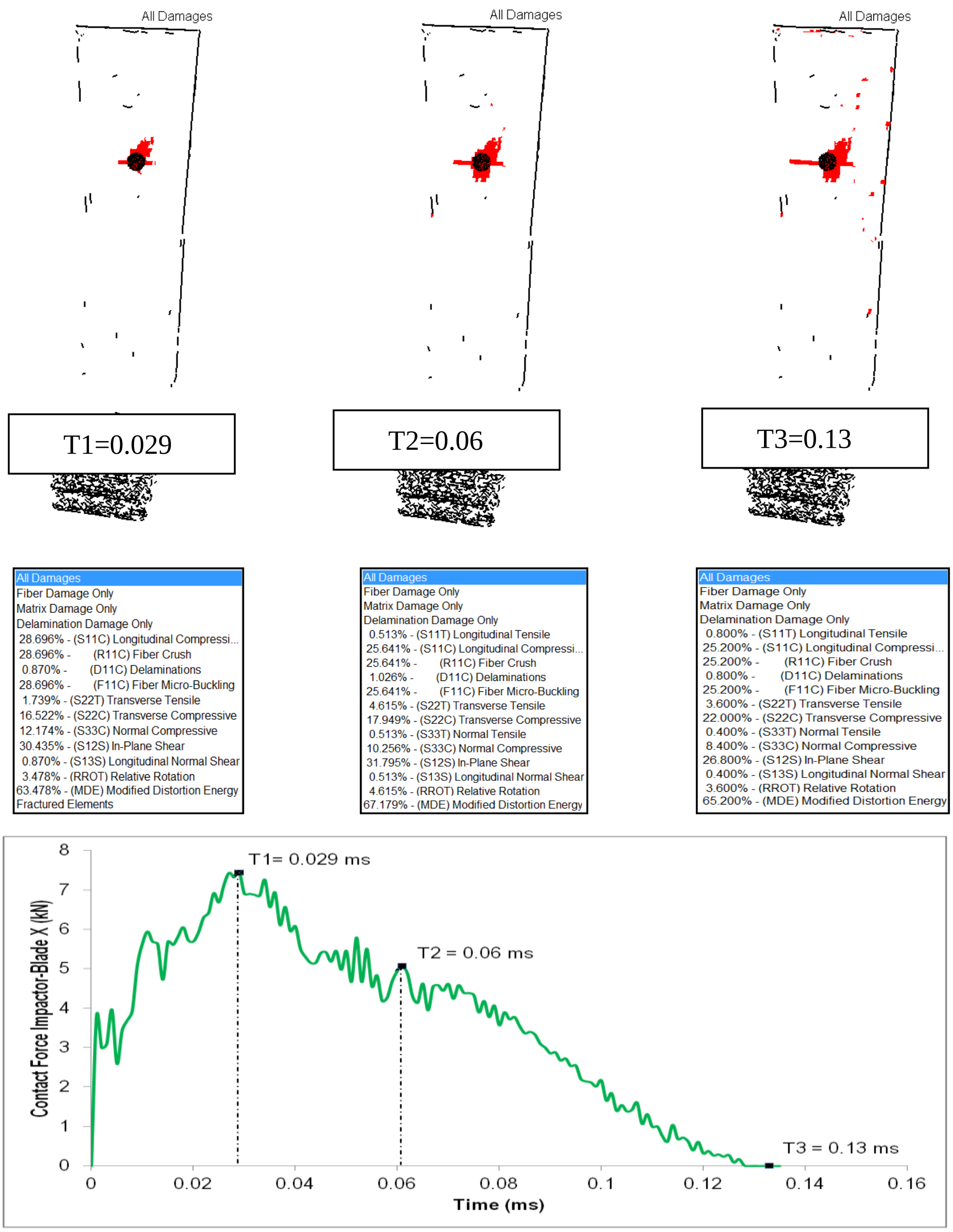


Figure 9 Damage propagation at 20J

4 Conclusion

GENOA using LS-DYNA user material (UMAT) was able to predict damage footprint after impact simulation. The accuracy of the results does not only rely on the simulations but also in the pre-processing of the experimental material data. MCQ-Composites generated fiber-matrix properties for the problem as well as calibrate the matrix stress-strain curve, in order to take into account material non-linearity during the analyses. Besides the limitations in experimental data, good trend in terms of deviation between different impact energy obtained for damage footprint size was achieved.

A methodology to perform impact simulation followed by standardized multi-scale material modeling. This process also creates a baseline for future works involving two step analyses such as impact followed by tension loading or impact followed by fatigue analysis. Results could be improved if more experimental data were available for both material characterization and experimental process.

It is interesting to characterize out-of-plane properties prior to complex simulations such as impact in order to predict damage more accurately. Exact values for fiber volume ratio and void volume ration are vital information in micro-mechanic simulations. Future work for the authors will be to perform the same type of simulations taking standard impact simulation into account by considering FEM validation.

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