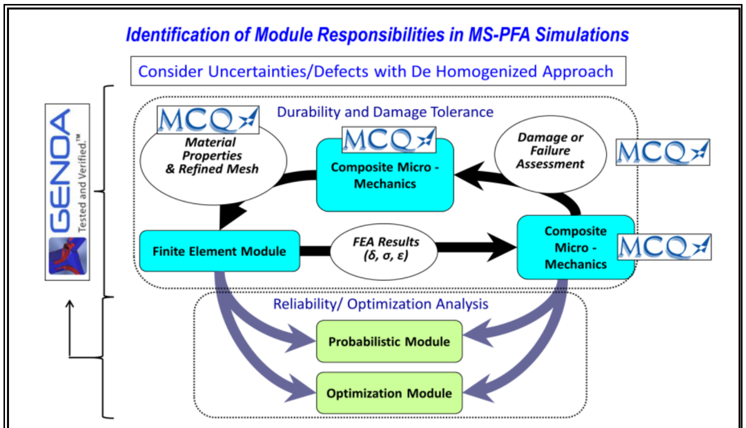
Damage Tolerant Composite Design Principles for Aircraft Components Under Static Service Loading Using Multi-Scale Progressive Failure Analysis

Challenge

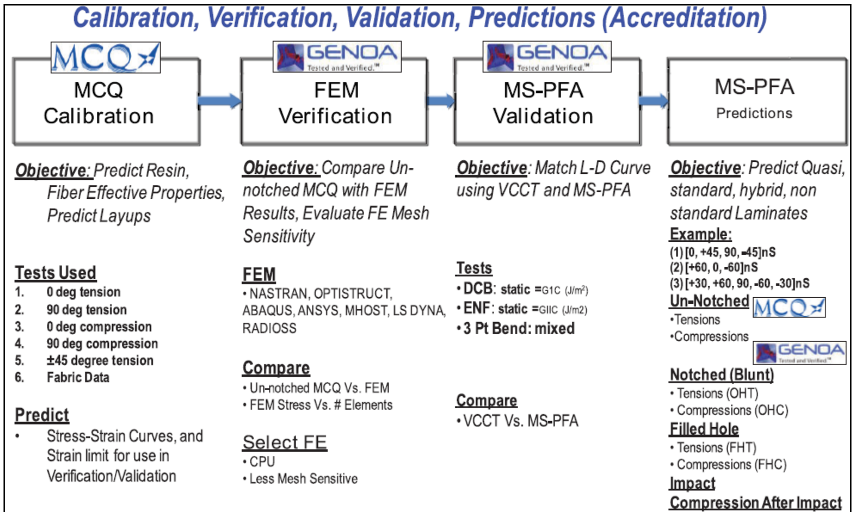


Functionality and Module Responsibilities of GENOA

The US Air Force places a high priority on Damage & Damage Tolerance (D&DT) and is committed to identify mechanisms to improve performance without compromising safety. In the past, this was only accomplished through testing. More recently, computational codes have been used to supplement testing. While it is clear that computational codes cannot entirely replace testing they can be validated against test to increase confidence associated with their use. In that regard, validation of software by blind prediction test serves two functions. First, it provides a platform to assess the accuracy of commercial software. Second, it provides confidence with regard to the approach and methodology used by the end user to find a particular solution. Against this background, the Air Force recently conducted an open competition to assess the predictive capabilities and boundaries of applicability of current models and design methodologies from selected companies across the globe. Materials and components were subjected to static and fatigue loads. Software tools were challenged to predict the results of those tests.

Solution

AlphaSTAR's GENOA software is capable of D&DT, life, and reliability predictions by means of Multi-Scale Progressive Failure Analysis (MS-PFA). The software augments the output of commercial FEM analysis to provide engineers with predictive technology to characterize and qualify advanced composites materials and structures considering manufacturing anomalies (i.e., matrix distortion, residual stress, fiber waviness, gaps, thickness effects), effects of defect shape, size and location, and scatter for "as-built/as-is" states of composite material and structure. The innovation in GENOA is on the integration of composite constituent micromechanics level progressive failure simulation with finite element structural analysis in a building block strategy. Here calibration, verification and validation correspond to finalizing a material model and comparing simple analysis to test before targeting a blind prediction.



Flow Process for MS-PFA

For the Air Force challenge, data sets for five ASTM tests for in-plane behavior were secured and used to calibrate the material model with MCQ Composites in support of the D&DT analysis. These tests included fiber volume ration, void volume ratio, longitudinal tension and compression; transverse tension and compression; and shear, both v-notch and +/-45 tension. Data was used to reverse engineer in-situ constituent (fiber and matrix) properties and matrix non-linearity, while accounting for voids. This information was then used to calibrate and verify the material model by analyzing properties of lamina and laminates and comparing the results against tests. Next, damage and fracture criteria were chosen and set for the rest of the prediction process. Here, damage corresponded to the lamina and fracture corresponded to the laminate.

Calibration Comparison

IM7/977-3 (Tape): FVR=70.6%; VVR=1.7%				
Material		IM7/977-3		
Property	Units	Test	MCQ	% Error
E11	[GPa]	193.39	193.46	0.03
E22	[GPa]	8.85	8.85	-0.03
E33	[GPa]	-	8.85	-
G12	[GPa]	4.67	4.67	0.06
G13	[GPa]	-	4.67	-
G23	[GPa]	-	2.46	-
v12	[-]	0.32	0.32	0.00
v23	[-]	-	0.54	-
v13	[-]	-	0.32	-
S11T	[MPa]	2877.79	2858.36	-0.68
S11C	[MPa]	1680.00	1691.25	0.67
S22T	[MPa]	53.60	52.88	-1.34
S22C	[MPa]	227.50	225.40	-0.92
S33T	[MPa]	-	52.88	-
S33C	[MPa]	-	225.40	-
S12S	[MPa]	99.69	99.28	-0.41
S13S	[MPa]	-	98.30	-
S23S	[MPa]	-	88.89	-

Post Damage Degradation 0.1%

Post Damage Degradation (Global)
- Damage Factor Tension (DFACTT) = 1.000000E-03
- Damage Factor Compression (DFACTC) = 1.000000E-03
- Damage Factor Shear (DFACTS) = 1.000000E-03
- Fracture Factor (FFACT) = 1.000000E-02

Output - Reverse Egineered Effective Matrix Properties

Effective Epoxy (977-3)			
Matrix Material Properties	Symbol	Effective	Units
Young's Modulus	Em	3.45	[GPa]
Poisson's Ratio	vm	0.41	[-]
Tension Strength	SmT	81.3	[MPa]
Compression Strength	SmC	350.2	[MPa]
Shear Strength	SmS	153.2	[MPa]

Output - Reverse Egineered Effective Fiber Properties

Effective Fiber (IM7)			
Fiber Material Properties	Symbol	Effective	Units
Longitudinal Young's Modulus	Ef11	277.1	[GPa]
Transverse Young's Modulus	Ef22	12.9	[GPa]
Poisson's Ratio	vf12	0.28	[-]
Poisson's Ratio	vf23	0.45	[-]
Shear Modulus	Gf12	10721	[MPa]
Shear Modulus	Gf23	4452	[MPa]
Longitudinal Tension Strength	Sf11T	4082	[MPa]
Longitudinal Compression Strength	Sf11C	2266	[MPa]

Strain Limits

Ply Strain Limit	Value
Eps11T	1.479E-02
Eps11C	1.500E-02
Eps22T	6.617E-03
Eps22C	3.003E-02
Eps33T	6.000E-03
Eps33C	3.003E-02
Eps12S	1.100E-01
Eps23S	1.50E-01
Eps13S	1.100E-01

Assumption
Eps33C=Eps22C
Eps13S=Eps12S

Matrix is anisotropic after damage

Calibration data/fiber/matrix properties for predictions

Validations were performed with 3-point-bend and DCB static tests using GENOA. The 3-point-bend validation simulation utilized an extremely simple shell model with no contact and the previously defined calibrated material inputs. The results were consistent with test data. In the case of the DCB (i.e. Mode I VCCT) validation, a 15,000 element finite element model consisting of 8-noded solid elements was established. This model included the number of plies, interlayer, boundary conditions and loading conditions. Once again simulation closely followed tests.

Analysis of the twelve blind and recalibrated predictions under static loading were undertaken with GENOA multi-scale progressive failure analysis with the support of MHOST, NASTRAN and ABAQUS. Results of both sets of predictions are summarized. Specimens consisted of un-notched tension, un-notched compression, open-hole tension, and open-hole compression. Specimen dimensions were length 160 mm, width 40 mm, and thickness 2 mm. Hole diameter was 6.5 mm. The composite specimen consists of 16 plies oriented as [0/45/90/-45]2S.

Twelve Blind Predictions

TEST DATA					Recalibration				Results Comparison			
ID	TYPE	Layup	Max Stress (MPa)	E (GPa)	Max Load (N)	Max Stress (MPa)	E (GPa)	CPU Time (s)	% DIFF SIG	Over or Under Predict	% DIFF E	Over or Under Predict E
CC-19	UNT	[0,45,90,−45]2S	866	60.5	47,086	912	67	209	5.34	Over	10.1	Over
CC-20	UNT	[+30,+60,90,−60,−30]2S	473	38	34,145	529	44	190	11.85	Over	15.7	Over
CC-21	UNT	[+60,0,−60]3S	1,005	59.5	58,539	1,008	67	88	0.28	Over	11.9	Over
CC-22	OHT	[0,45,90,−45]2S	538	48.3	41,497	533	56	2,673	0.95	Under	16.6	Over
CC-23	OHT	[+30,+60,90,−60,−30]2S	404	32.4	37,046	380	39	4,761	5.84	Under	19.3	Over
CC-24	OHT	[+60,0,−60]3S	518	48.8	52,121	574	57	2,334	10.71	Over	17.6	Over
CC-25	UNC	[0,45,90,−45]2S	605	48	35,533	688	67	129	13.82	Over	38.8	Over
CC-26	UNC	[+30,+60,90,−60,−30]2S	392	33.5	36,230	562	44	129	43.19	Over	31.3	Over
CC-27	UNC	[+60,0,−60]3S	765	48.9	32,268	556	67	141	27.4	Under	36.2	Over
CC-51	OHC	[+60,0,−60]3S	376	44.4	30,411	349	56	10,344	7.11	Under	26.5	Over
CC-52	OHC	[0,45,90,−45]2S	338	44.5	28,702	371	56	11,809	9.54	Over	26.3	Over
CC-53	OHC	[+30,+60,90,−60,−30]2S	295	30.1	34,604	358	40	11,346	21.34	Over	32	Over

Twelve Recalibrated Predictions

TEST DATA					Recalibration				Results Comparison			
ID	TYPE	Layup	Max Stress (MPa)	E (GPa)	Max Load (N)	Max Stress (MPa)	E (GPa)	CPU Time (s)	% DIFF SIG	Over or Under Predict	% DIFF E	Over or Under Predict E
CC-19	UNT	[0,45,90,−45]2S	866	60.5	42,758	828	66	237	4.34	Under	8.9	Over
CC-20	UNT	[+30,+60,90,−60,−30]2S	473	38	32,752	508	43	262	7.29	Over	13.1	Over
CC-21	UNT	[+60,0,−60]3S	1,005	59.5	54,790	944	67	168	6.14	Under	12.6	Over
CC-22	OHT	[0,45,90,−45]2S	538	48.3	42,052	543	57	2,975	0.9	Over	17.2	Over
CC-23	OHT	[+30,+60,90,−60,−30]2S	404	32.4	39,208	405	39	6,243	0.31	Over	19.4	Over
CC-24	OHT	[+60,0,−60]3S	518	48.8	37,902	435	58	2,256	16.04	Under	18	Over
CC-25	UNC	[0,45,90,−45]2S	605	48	31,495	610	44	200	0.86	Over	7.3	Under
CC-26	UNC	[+30,+60,90,−60,−30]2S	392	33.5	28,311	439	30	223	11.89	Over	9.6	Under
CC-27	UNC	[+60,0,−60]3S	765	48.9	27,834	479	45	215	37.4	Under	7.5	Under
CC-51	OHC	[+60,0,−60]3S	376	44.4	33,083	380	39	2,819	1.05	Over	12.1	Under
CC-52	OHC	[0,45,90,−45]2S	338	44.5	28,137	363	38	1,366	7.39	Over	13.8	Under
CC-53	OHC	[+30,+60,90,−60,−30]2S	295	30.1	31,254	323	27	3,516	9.59	Over	9.2	Under

Results & Conclusion

- Calibration of the fiber/matrix properties was performed using in plane test data.
- Validation was accomplished using 3pt bend and DCB test data for laminates.
- Static strength had an average error of 12.9% between simulation and test data.
- Static stiffness error was 23.5%.
- Recalibration efforts showed an improved average of 9.2% for strength and 12.4% for stiffness computations.
- Damage at 60–75% and 90% of max loading was comparable with experimental results.
- Methodology employed (1) GENOA with MHOST; (2) GENOA with NASTRAN and (3) ABAQUS solver using GENOA as a material subroutine.

Key Highlights & Benefits
Product: GENOA, MCQ-Composites, ABAQUS UMAT
Industry: Aerospace
Application: Blind Prediction for Static Analysis Using Building Block Approach
Benefits: Modeling and simulation of complex parts and materials, Guides test by analysis to reduce testing up to 50%, Delivers Greater Accuracy with Minimal Computational Overhead

Related Publication

Damage Tolerant Composite Design Principles for Aircraft Components under Static Service Loading Using Multi-Scale Progressive Failure Analysis. Journal of Composite Materials, vol. 51, 10: pp. 1393-1419.