JAMS

JOINT ADVANCED MATERIALS & STRUCTURES
CENTER OF EXCELLENCE

Composite Damage Material Modeling for Crash Simulation: MAT54 & the Efforts of the CMH-17 Numerical Round Robin

2014 Technical Review

Bonnie Wade (UW)

Prof. Paolo Feraboli

AMTAS (JAMS) Crashworthiness Research Contributions

Experiment

- Material property testing of AGATE material system, quasi-static
- Crush testing of flat coupons & eight element-level geometries, quasi-static
- Three journal articles published on experimental work

Analysis

- LS-DYNA composite damage material model MAT54 single element characterization
- LS-DYNA crush simulations of eight element-level geometries
- MAT54 source code modifications & material modeling improvements
- LS-DYNA MAT54 CMH-17 Crashworthiness Numerical RR entry
- Summary report for CMH-17 Numerical RR
- One journal article published, two in review; Two FAA Technical Reports delivered

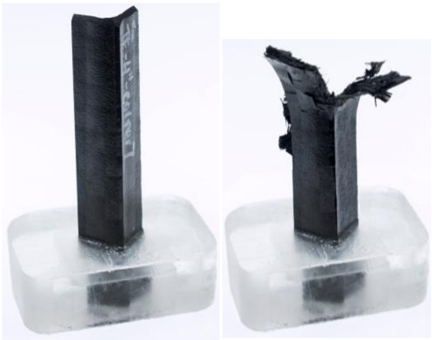
Educational Module

- 2012 FAA Level II Course classroom lecture: presentation notes & video provided
- One FAA Technical Report delivered

Challenges in composites crashworthiness

- Composites are non homogenous – damage can initiate and propagate in many ways, specifics of which cannot be predicted
- Many different failure mechanisms can occur (fiber breakage, matrix cracking, shearing, delamination, etc.) and damage growth is not self-similar

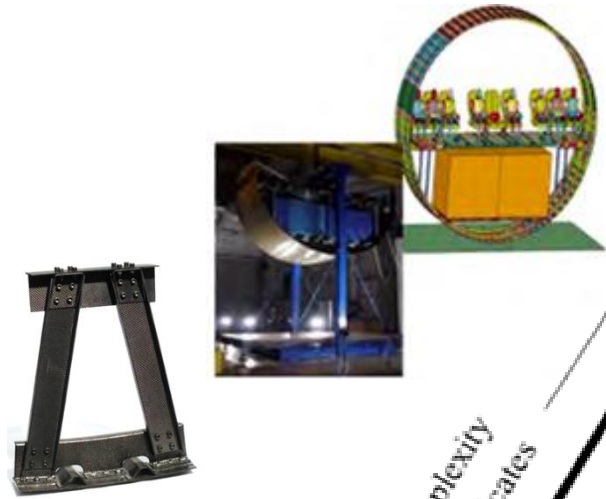


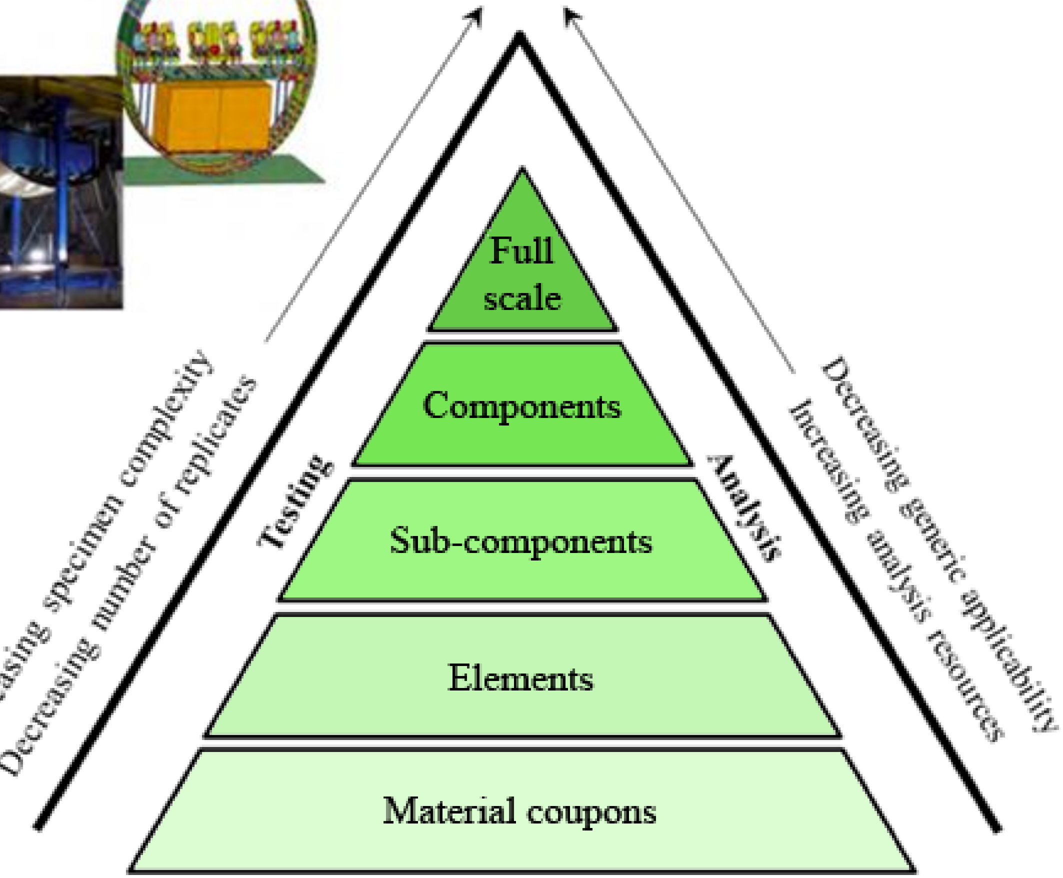


- Current FEA technology cannot capture details of individual failure modes, but needs to make approximations. The key is to know how to make the right approximations
  - Material failure is treated macroscopically: cannot account for differences between failure mechanisms
- In this research, the Building Block Approach is employed to develop an experimental program which supports the development of the composite structure crash analysis
- The development of the material model to simulate composites crash damage is the focus

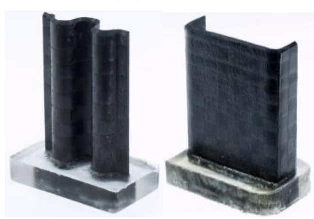
Building Block Approach applied to composites crashworthiness

- Crash analysis is supported by test evidence at numerous structural levels
- The material model is often developed using coupon-level experimental data

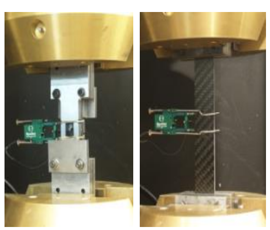




Crush element simulated with material model



Standardized material properties input directly into material model



AUTOMOBILI LAMBORGHINI ADVANCED COMPOSITE STRUCTURES LABORATORY

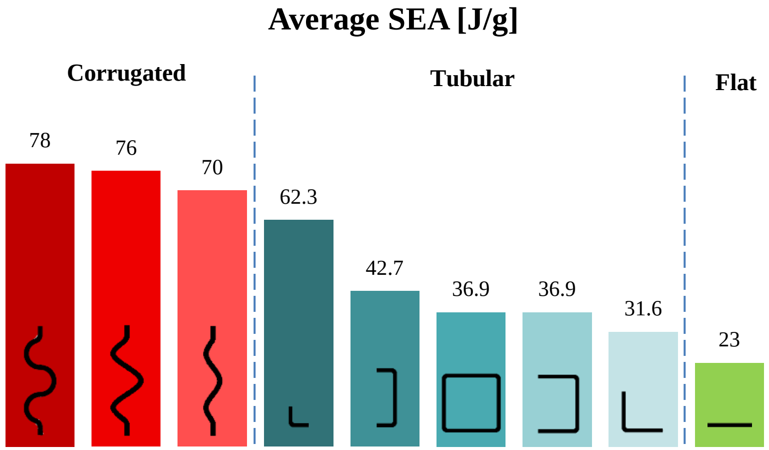
CECAM

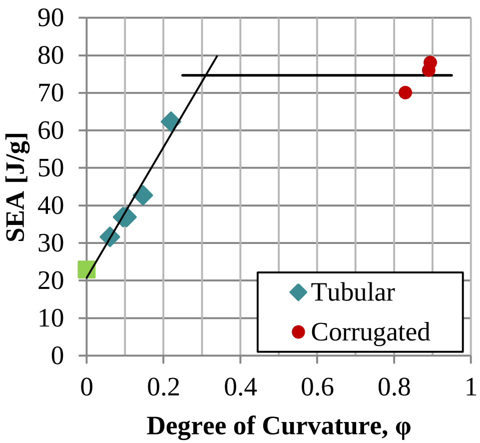
JAMS JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

AMTAS Advanced Materials in Transport Aircraft Structures

Key findings from element-level crush experiments

- Flat coupon-level crush tests and eight different element-level crush tests performed on a single material system & lay-up
- Specific energy absorption (SEA) results varied from 23-78 J/g, depending on geometry
  - SEA depends directly on geometric curvature





- The energy absorption capability of a material, measured by SEA, is not a material property
  - Cannot be experimentally quantified at the coupon-level

Composite damage material models

- Composites are modeled as orthotropic linear elastic materials within a failure surface
  - Linear elastic behavior defined by coupon-level material properties
- Failure surface is defined by the failure criteria
  - Failure criteria often require ultimate stress values measured from coupon-level experiments
- Beyond the failure surface, damage is modeled in one of two ways:
  - Progressive Failure Model (PFM): Specific ply properties go to zero, ply by ply failure until all plies have failed and element is eroded
  - Continuum Damage Mechanics (CDM): Uses damage parameters to degrade ply properties in a continuous form
- Ultimate material failure (i.e. element erosion) also requires a set of criteria

CMH-17 Crashworthiness WG Numerical RR

- Initiated in 2008 by Dr. Rassaian (Boeing Research & Technology), the Numerical Round Robin set out to evaluate the predictive capabilities of commercial composite crash modeling codes
- Each approach has own material model (includes failure criteria & damage model) element type, contact definition, crushing trigger mechanism, etc.

CMH17 COMPOSITE MATERIALS HANDBOOK

Participant	Company/ Organization	FE Code	Material model	Element
G. Barnes	Engenuity	Abaqus	C-Zone	Single shell
P. Feraboli	University of Washington	LS-DYNA	MAT54	Single shell
R. Foedinger	Material Sciences Corp.	LS-DYNA	MAT162	3D brick
K. Indermuehle	Simulia	Abaqus Explicit	VUMAT	Stacked shells
A. Johnson	DLR	PAM-CRASH	MAT131	Stacked shells
J.B. Mouillet	Altair Engineering	Radioss	Crasurv	Stacked shells
M. Rassaian	Boeing Research & Technology	LS-DYNA	MAT58	Single shell

- Round I: simulate corrugated element-level specimen crushing
- Round II: simulate five tubular element-level specimens crushing

LS-DYNA MAT54 composite damage model

- MAT54 is a progressive failure model for shell elements
- Four mode-based failure criteria for “fiber” (axial) and “matrix” (transverse) failure in tension and compression (Hashin [1] failure criteria as modified by Chang/Chang [2])
- Element erosion based on maximum strain values

- Most input parameters are derived from standardized coupon-level experiments
  - Tension/Compression and shear: modulus, strength, strain to failure
- Limited number of other parameters that cannot be measured experimentally, and need to be calibrated by trial and error
- Ideal candidate for large-scale crash simulation

*MAT_054 (ENHANCED_COMPOSITE_DAMAGE)

mid	**ro**	**ea**	**eb**	**ec**	**prba**	~~**prca**~~	~~**prcb**~~
1	1.50E-4	1.84E+7	1.22E+6	0.0	0.02049	0.0	0.0
gab	~~**gbc**~~	~~**gca**~~	~~**kf**~~	**aopt**			
6.10E+5	6.10E+5	6.10E+5	0.0	0.0			
xp	**yp**	**zp**	**a1**	**a2**	**a3**	**mangle**	
0.0	0.0	0.0	0.0	0.0	0.0	0.0	
v1	**v2**	**v3**	**d1**	**d2**	**d3**	**dfailm**	**dfails**
0.0	0.0	0.0	0.0	0.0	0.0	0.024	0.03
tfail	**alph**	**soft**	**fbrt**	**ycfac**	**dfailt**	**dfailc**	**efs**
1.1530E-9	0.1	0.0	0.5	1.2	0.0174	-0.0116	0.0
xc	**xt**	**yc**	**yt**	**sc**	**crit**	**beta**	
213000	319000	28800	7090	22400	54	0.5	

1. Constitutive properties: RO, EA, EB, EC, PRBA, PRCA, PRCB, GAB, GBC, GCA, KF

2. Local material axes: AOPT, XP, YP, ZP, A1-A3, MANGLE, V1-V3, D1-D3

3. Shear weighing factors: ALPH, BETA

4. Deletion parameters: DFAILM, DFAILS, TFAIL, DFAILT, DFAILC, EFS

5. Damage factors: SOFT, FBRT, YCFAC

6. Material strengths: XC, XT, YC, YT, SC

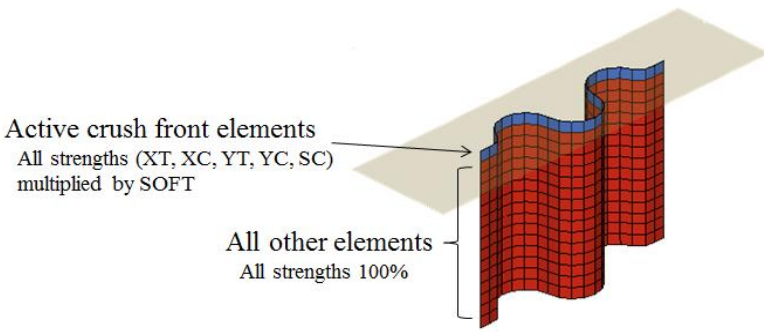
7. Failure criterion selection: CRIT

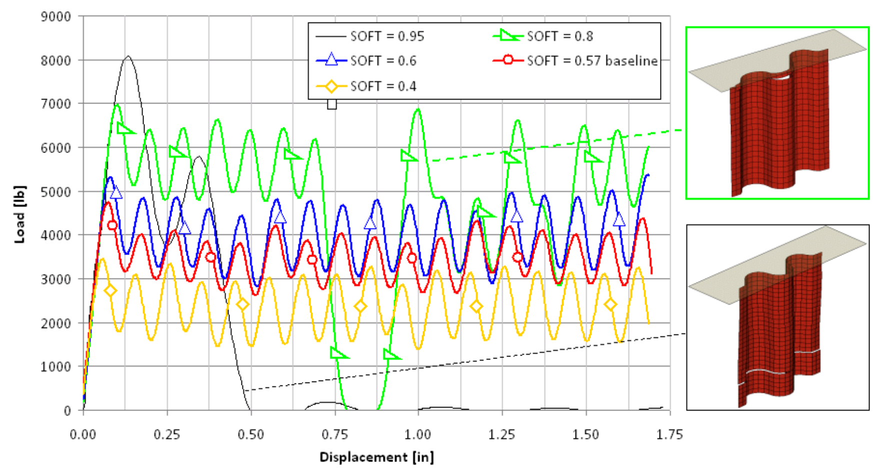
[1] Z. Hashin, “Failure criteria for unidirectional fiber composites,” *Journal of Applied Mechanics*, vol. 47, pp. 329-334, 1980.

[2] F. Chang and K. Chang, “A progressive damage model for laminated composites containing stress concentrations,” *Journal of Composite Materials*, vol. 21, pp.834-855, 1987.

MAT54: CMH-17 Round I challenge

- Given only coupon-level material property data, the model is developed successfully but could not predict the crushing behavior of the sinusoid
- Sensitivity studies on the MAT54 input parameters revealed that one of the non-experimentally derived parameters, SOFT, directly influences the post-failure damage simulated in crush-front elements, thereby directly changing the average crushing load



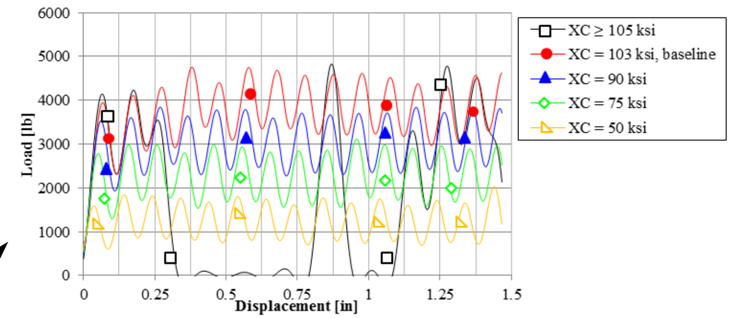


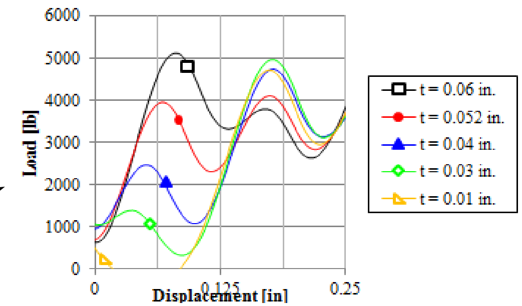
- Without element-level crush data, the correct value of SOFT cannot be estimated
- The other non-experimental parameters (e.g. ALPH, BETA, YCFAC, FBRT) were found to not have an influence on the crush element simulation

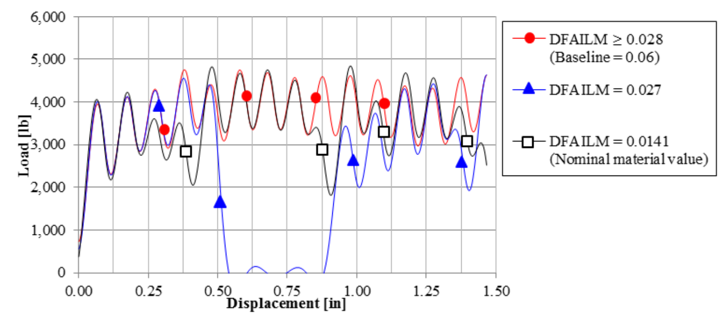
AUTOMOBILI LAMBORGHINI ADVANCED COMPOSITE STRUCTURES LABORATORY   CECAM   JAMS JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE   AMTAS Advanced Materials in Transport Aircraft Structures

MAT54: Parametric studies

- Using the Round I specimen, sensitivity studies were performed on all MAT54 input parameters as well as other relevant modeling parameters (contact model, mesh size, loading speed, etc.) (Published 2011 [3])
- These studies reveal important or sensitive parameters
  - Some results are expected: influence of compressive axial properties, XC and DFAILC, upon average crushing load
  - Some results are revealing: influence of contact definition LP curve on stability & influence of crush trigger elements (first row) thickness on initial load peak
  - Some results are unexpected: influence of transverse failure strain, DFAILM, on stability; *required enlargement beyond experimentally measured value for stability*



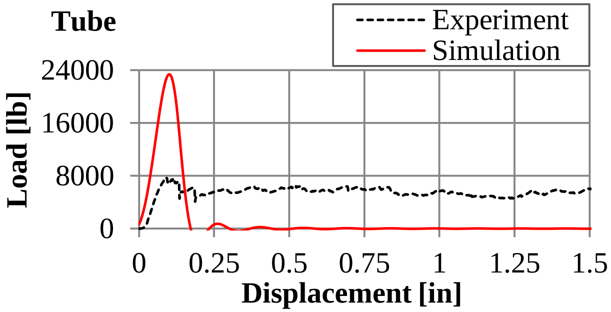


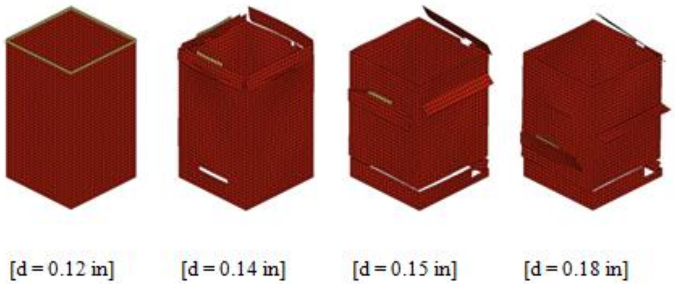


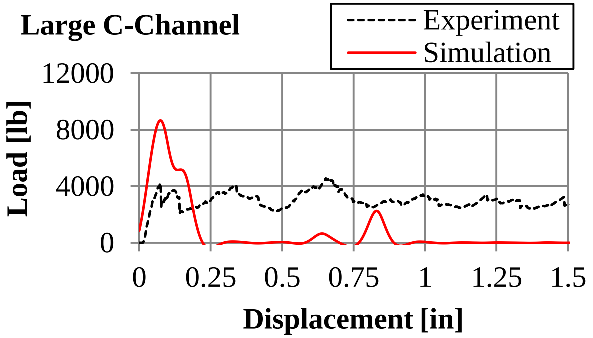
[3] P. Feraboli, B. Wade, F. Deleo, M. Rassaian, M. Higgins and A. Byar, "LS-DYNA MAT54 modeling of the axial crushing of a composite tape sinusoidal specimen," *Composites: Part A,* vol. 42, pp. 1809-1825, 2011.

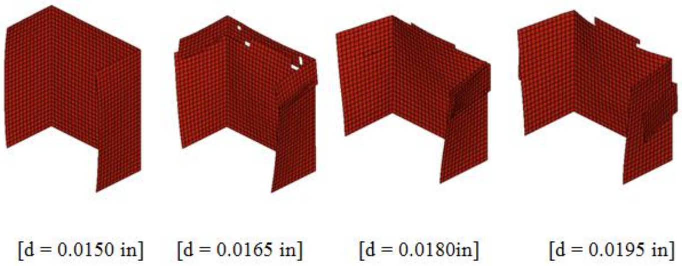
MAT54: CMH-17 Round II challenge

- Using the modeling strategy developed in Round I, the new Round II geometries could not be modeled with the material card as-is
  - No changes were made to the modeling strategy or material card
  - *Note, initial predictions were made without experimental data, but experimental data is shown for scale*



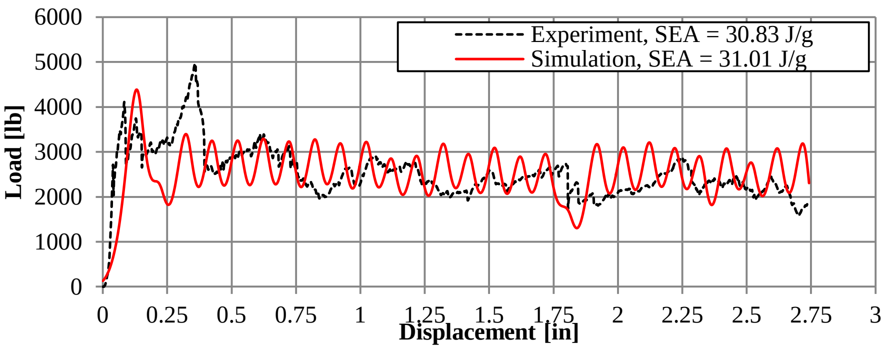


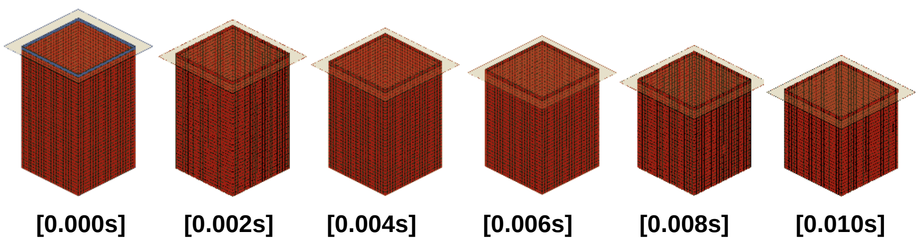


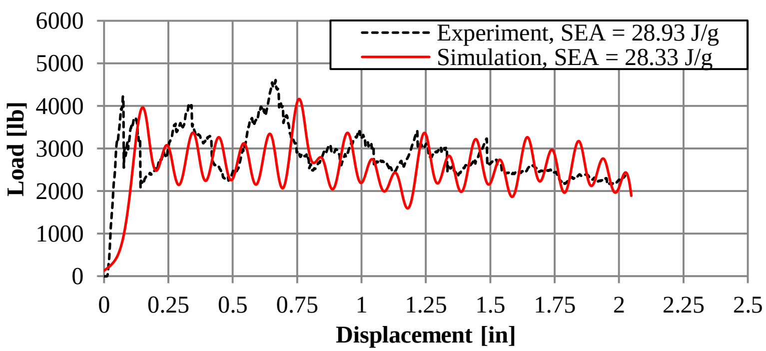


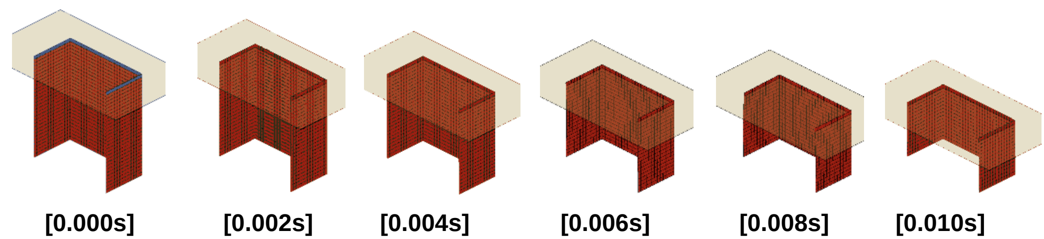
Using element-level data for model calibration

- With the experimental crush data of the Round II specimens, the material model was calibrated such that it simulated the experiment
  - SOFT was calibrated such that the average crushing load was captured
  - Trigger thickness was calibrated such that initial load peak was captured
- With these two calibrations, all specimens were successfully modeled







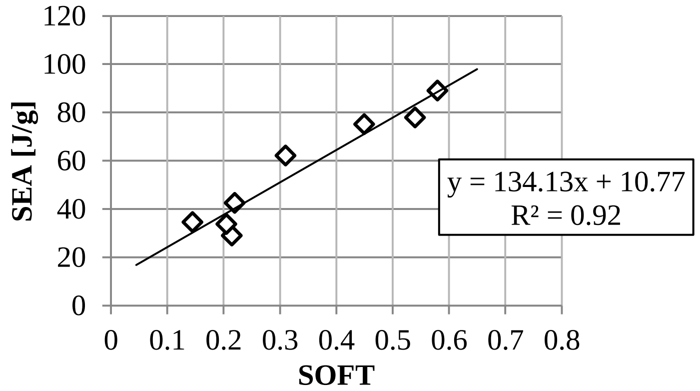


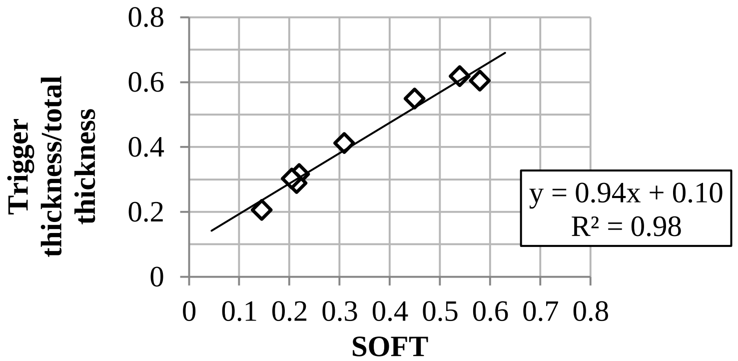
Element-level model calibration results

- Given element-level crush data, MAT54 can successfully be calibrated to simulate crushing failure
  - Recall that experimentally the energy absorption capability of a material can only be described at the element-level

Geometry	*Trigger Thickness [in]*	*SOFT*	*Single Test SEA [J/g]*	*Numeric SEA [J/g]*	*Error*
SC Sinusoid	0.044	0.580	88.98	89.08	0.1%
High Sinusoid	0.045	0.540	77.84	77.28	-0.7%
Low Sinusoid	0.040	0.450	75.01	74.13	-1.2%
Tube	0.015	0.145	34.55	34.99	1.3%
Large Channel	0.021	0.215	28.93	28.33	-2.1%
Small Channel	0.023	0.220	42.49	42.49	0.0%
Large Corner	0.022	0.205	33.71	33.43	-0.8%
Small Corner	0.030	0.310	62.11	62.44	0.5%

- As a result of this investigation, a linear trend was developed between the experimentally measured SEA and the calibrated MAT54 SOFT parameter
  - Given the known element-level SEA, an approximation for SOFT can be made
- A linear trend is also shown between SOFT and the trigger thickness reduction
  - SOFT does not apply to the initial row of elements; the trigger row is reduced in thickness to in effect apply the same strength knock-down as SOFT





AUTOMOBILI LAMBORGHINI ADVANCED COMPOSITE STRUCTURES LABORATORY

CECAM

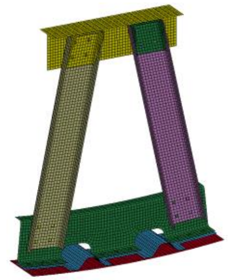
JAMS JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

Relevance within BBA

- The development, calibration, and validation of the MAT54 material model for crush simulation can be described within the context of the lower levels of the BBA

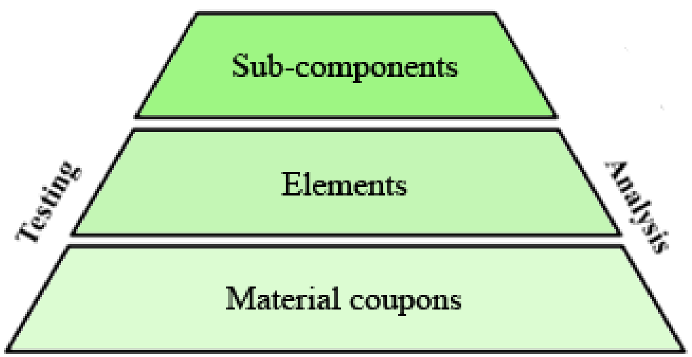
Sub-component test (subfloor section shown)



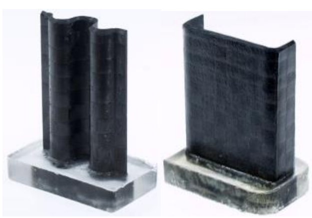
MAT54 validation: material model unchanged in sub-component simulation

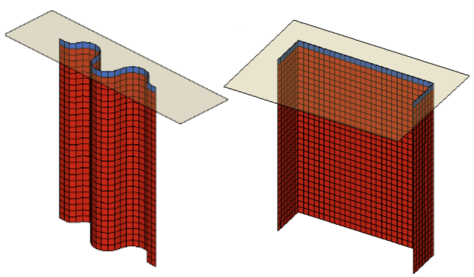
Courtesy Max Spetzler

Crush element-level tests to characterize full SEA capability of material

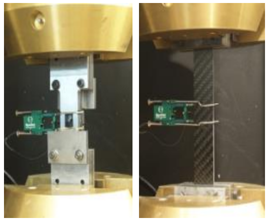


MAT54 calibration: SOFT parameter and trigger thickness calibrated using exp. measured SEA





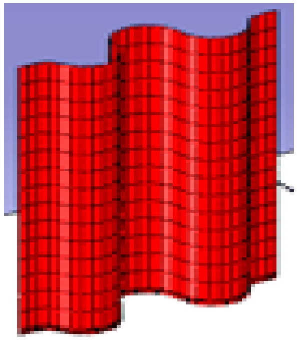
Tension, compression, and shear coupon-level tests



MAT54 development: coupon-level test data input directly into MAT54 (no simulation)

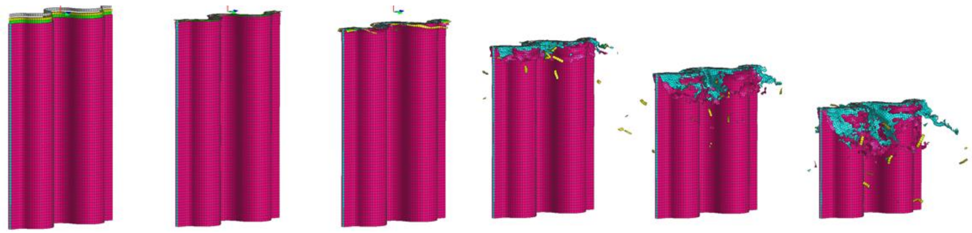
CMH-17 RR: G. Barnes (Engenuity)

- Abaqus Explicit model using a progressive damage material model with CZone, a failure criterion especially developed for crush modeling
- CZone use crush stress values measured from element-level crush tests to determine failure initiation, in addition to Tsai-Wu failure criterion
- Material damping and energy release rate also measured from coupon-level tests and input into material model
  - Energy release rate values used in post-failure damage model
- Single shell element approach



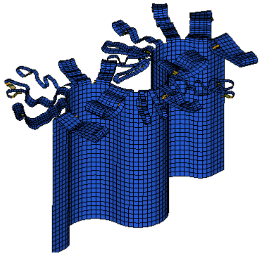
CMH-17 RR: A. Johnson (DLR)

- PAM-CRASH model using stacked shell elements to simulate lamina clusters with cohesive elements in between to allow for delamination modeling
- Damage mechanics material model which uses damage factors measured from coupon-level fatigue testing
- Maximum strain and maximum shear energy failure criteria
- Cohesive elements have an additional failure criterion defined using coupon-level G_{IC} and G_{IIC} tests which require coupon-level simulation calibrations
- Numerical trigger mechanism is calibrated using element-level test data such that the correct failure mechanism is triggered



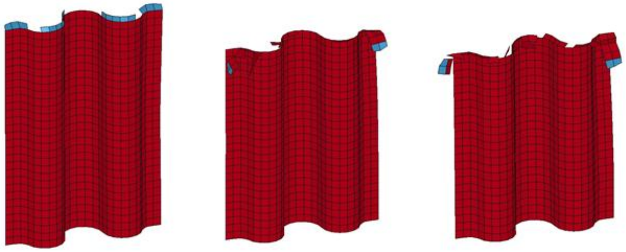
CMH-17 RR: J.B. Mouillet (Altair Engineering)

- RADIOSS model which uses CRASURV orthotropic material law
  - Based on a visco-elastic-plastic, non-linear material
- Uses non-linear Tsai-Wu failure criterion for failure initiation
- Non-linearities following failure are modeled through “plastic work” variable, which simulates the diffusion of damage within the material
- Ultimate failure is determined by maximum plastic work and maximum tensile and residual strains
- Many input parameters require curve fitting against non-linear coupon-level data
- Test data for some parameters difficult to acquire, and is assumed
- Uses stacked shells



CMH-17 RR: M. Rassaian (BR&T)

- LS-DYNA simulation with MAT58 damage mechanics material model
- Failure criteria defined using maximum stress values from coupon-level tests
- Damage model includes residual stress factors which must be calibrated using element-level crush data
- Final failure is determined from maximum strain values measured from coupon-level tests
- SOFT parameter also available for MAT58
- Single shell element approach



AUTOMOBILI LAMBORGHINI ADVANCED COMPOSITE STRUCTURES LABORATORY
CECAM
JAMS JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE
A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

Conclusion

- The Building Block Approach is applied to the development of a crash model for composite structures
- Experimental results have shown the need to characterize the energy absorbing capability of the material at the element-level
- Simulation results using LS-DYNA composite damage material model MAT54 have demonstrated its capability in the lower levels of the BBA, and promising utility at higher levels of the BBA
- Efforts of the CMH-17 Numerical RR have also demonstrated the need to use element-level test data to develop the material model specifically for crush simulation
  - i.e. material model cannot be defined simply from coupon-level data

Acknowledgments

- Dr. Larry Ilcewicz, Allan Abramowitz, Curt Davies

Federal Aviation Administration

- Dr. Mostafa Rassaian

Boeing Research & Technology

- Crashworthiness Working Group Round Robin participants

CMH-17 (former MIL-HDBK-17)

End of Presentation.

Thank you.

AUTOMOBILI LAMBORGHINI
ADVANCED COMPOSITE STRUCTURES LABORATORY

JAMS
JOINT ADVANCED MATERIALS & STRUCTURES
CENTER OF EXCELLENCE

A Center of Excellence
AMTAS
Advanced Materials in Transport Aircraft Structures

CECAM
center of excellence for composites and advanced materials