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

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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
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
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 its own material model (includes failure criteria & damage model) element type, contact definition, crushing trigger mechanism, etc.

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<th>Participant</th>
<th>Company/ Organization</th>
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<th>Material model</th>
<th>Element</th>
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<td>Boeing Research &amp; Technology</td>
<td>LS-DYNA</td>
<td>MAT58</td>
<td>Single shell</td>
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- Round I: simulate corrugated element-level specimen crushing
- Round II: simulate five tubular element-level specimens crushing
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

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.
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; \textit{required enlargement beyond experimentally measured value for stability}

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
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

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
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.
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
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
- 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
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.