Application of the MAT 213 Composite Impact Model to NASA Problems of Interest

Robert K. Goldberg, Trenton M. Ricks, Troy Lyons, Javier Buenrostro
NASA Glenn Research Center, Cleveland, Ohio

Jacob Putnam
NASA Langley Research Center, Hampton, Virginia

Daniel Slaughter
Iowa State University, Ames, Iowa

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Background and Motivation

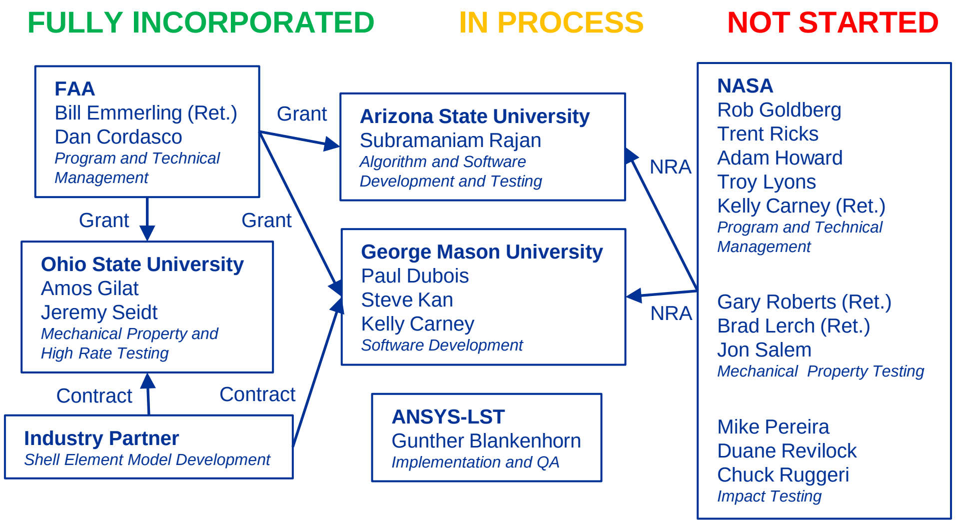
- Outcome of 2012 LS-DYNA Aerospace Working Group (AWG) (Industry, Government) study on limitations in impact modeling of composites
- Desired model requirements identified
- New consortium formed in 2012
- **Goal** - create a composite material model general enough to
  - Model the wide range of material properties and architectures found in PMC's
  - Recreate all of the behavior that can be found in material property tests (including tests that are not typically performed)
- **Status** - ongoing development (FAA), fully implemented into LS-DYNA dev, QA and LS-DYNA R13
- Multiple systems modeled

Model Maturity

T800/F3900 tape (carbon, epoxy)
IM7/8552 tape (carbon, epoxy)
Hybrid carbon/Kevlar, epoxy plain weave
Hexforce 282/SC-780 plain weave (carbon, epoxy)
3MDCP 3D woven (hybrid carbon/phenolic tows, phenolic)

Desired Model Requirements

- Generalized tabulated input, stress strain curve for non-damage related behavior (with limited or no curve fitting required by user)
- Input parameters based upon standard mechanical property tests
- Effects of strain rate need to be accounted for in a flexible, unified manner accounting for anisotropy of rate effects.
- Temperature dependency
- Strain based damage and failure parameters
- Failure parameters adjusted for mesh size, i.e. mesh regularization
- Explicit modeling of interlaminar delamination via tiebreak contact and cohesive zone elements
- Shell and solid element implementations (through thickness properties can be important)
- Must be computationally extremely fast



Deformation Model

Tsai-Wu failure criteria generalized to a yield function with 12 coefficients (F) determined from tension, compression, shear and off-axis tests

$$f(\boldsymbol{\sigma}) = a + \begin{pmatrix} F_1 & F_2 & F_3 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{zx} \end{pmatrix} + \begin{pmatrix} \sigma_{xx} & \sigma_{yy} & \sigma_{zz} & \sigma_{xy} & \sigma_{yz} & \sigma_{zx} \end{pmatrix} \begin{pmatrix} F_{11} & F_{12} & F_{13} & 0 & 0 & 0 \\ F_{12} & F_{22} & F_{23} & 0 & 0 & 0 \\ F_{13} & F_{23} & F_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & F_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & F_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & F_{66} \end{pmatrix} \begin{pmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{zx} \end{pmatrix}$$

- Coefficients determined from tension, compression, shear and off-axis tests
- Values of coefficients vary as plastic strain evolves. Tabulated stress-strain curve input used to define evolution

Non-associative flow rule applied with 9 independent constants

$$h = \sqrt{H_{11}\sigma_{xx}^2 + H_{22}\sigma_{yy}^2 + H_{33}\sigma_{zz}^2 + 2H_{12}\sigma_{xx}\sigma_{yy} + 2H_{23}\sigma_{yy}\sigma_{zz} + 2H_{31}\sigma_{zz}\sigma_{xx} + H_{44}\sigma_{xy}^2 + H_{55}\sigma_{yz}^2 + H_{66}\sigma_{zx}^2}$$

$$\dot{\boldsymbol{\varepsilon}}^p = \dot{\lambda}\frac{\partial h}{\partial \boldsymbol{\sigma}} \qquad \dot{W}_p = \boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}}^p = \boldsymbol{\sigma} : \dot{\lambda}\frac{\partial h}{\partial \boldsymbol{\sigma}} = h\dot{\lambda}$$

Damage Model

- Generalized damage laws (84 possible parameters) that model pre-peak or post-peak damage behavior
- Simulates nonlinear unloading and local softening often observed in composites
- Strain equivalent formulation is desired to permit plasticity and damage calculations to be uncoupled
  - Total, elastic, and plastic strains assumed to be equal in actual and effective stress spaces
  - Permits all plasticity calculations to be performed in effective stress space
- Effective stresses related to actual stresses by use of a diagonal damage tensor (M)
- Multiplicative reduction in modulus and stress
- Pre-peak damage: modulus reduction measurements
- Post-peak damage: assumed based on strength reduction

$$\boldsymbol{\sigma} = \mathbf{M}\boldsymbol{\sigma}_{eff}$$

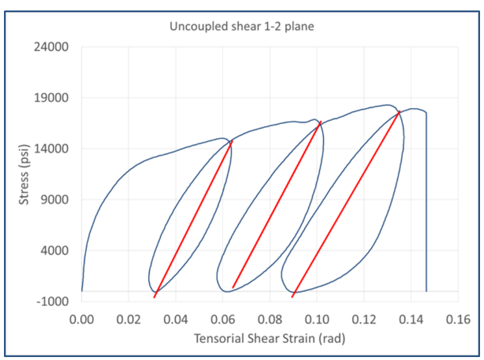
$$E_{xx}^{dxx} = \left(1 - d_{xx}^{xx}\left(\varepsilon_{xx}^{p}\right)\right)E_{xx}^{dyy} = \left(1 - d_{xx}^{xx}\left(\varepsilon_{xx}^{p}\right)\right)\left(1 - d_{yy}^{xx}\left(\varepsilon_{yy}^{p}\right)\right)E_{xx}$$

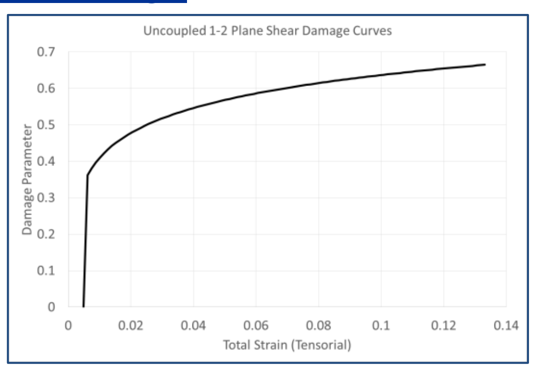
$$\sigma_{xx} = \left(1 - d_{xx}^{xx}\right)\left(1 - d_{yy}^{xx}\right)\left(1 - d_{xy}^{xx}\right)\sigma_{xx}^{eff}$$

$$\sigma_{yy} = \left(1 - d_{xx}^{yy}\right)\left(1 - d_{yy}^{yy}\right)\left(1 - d_{xy}^{yy}\right)\sigma_{yy}^{eff}$$

$$\sigma_{xy} = \left(1 - d_{xx}^{xy}\right)\left(1 - d_{yy}^{xy}\right)\left(1 - d_{xy}^{xy}\right)\sigma_{xx}^{eff}$$

Pre-peak Damage





Post-peak Damage

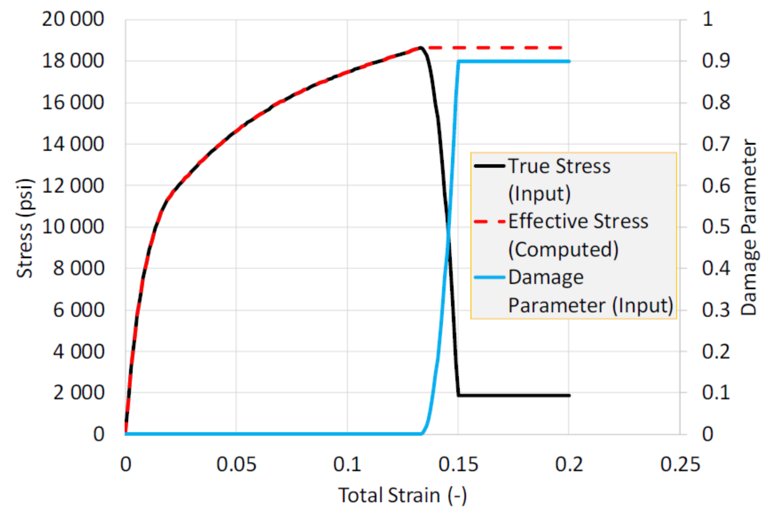
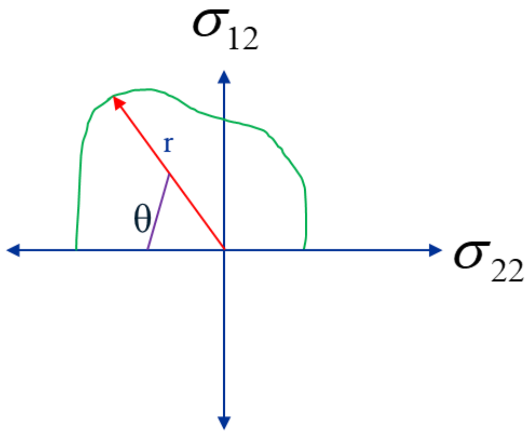


*Figure from *MAT_213 User Guide

Failure Model

- Analytical failure criteria: Tsai-Wu, Puck
- Tabulated failure criteria: **Generalized Tabulated Failure Criterion (GTFC)**, Point Cloud Failure Criterion
- Tabulated approach can allow for arbitrarily shaped failure surfaces
- Results are not mesh objective (to be implemented)
- GTFC
  - Stress or strain-based parameter values
  - In-plane failure surfaces
    - Arbitrary number of 1-direction normal stresses
    - Angle/radius pairs for each 1-direction stress
      - From 2-direction normal and 12-shear stresses or strains
  - Out-of-plane failure surfaces
    - Arbitrary number of 3-direction normal stresses
    - Angle/radius pairs for each 3-direction stress
      - From 23-shear and 13-shear stresses or strains
    - Not required for shell elements

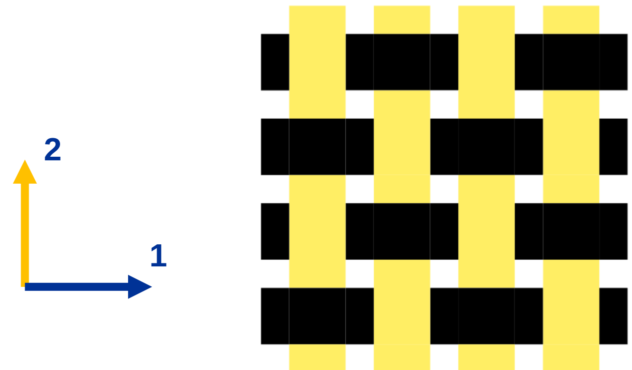


Structural Energy Absorber Modeling

Warp and fill fibers:

T300 3K carbon tows

Kevlar 49 3K tows

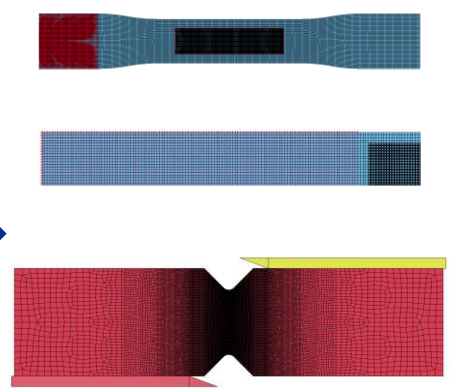


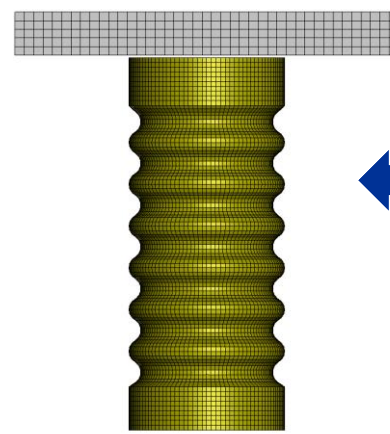
Matrix:

Epon 828 epoxy/Epikure 3223 hardener (thermoset)

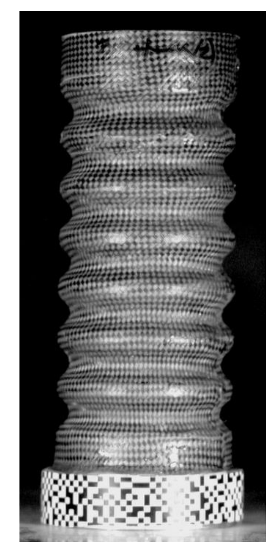
Iowa State University (NASA EPSCoR Award)

LS-DYNA explicit finite element modeling using *MAT_213



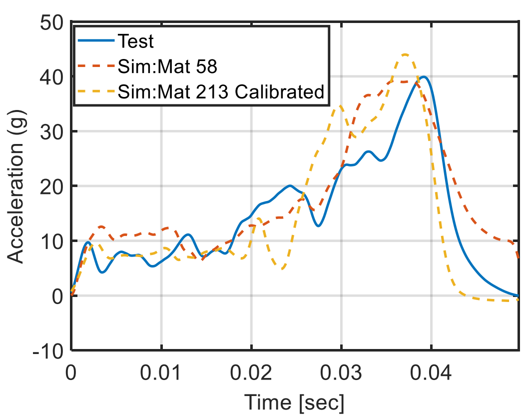


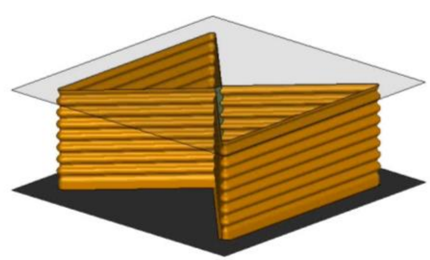
NASA LaRC Landing and Impact Research Facility

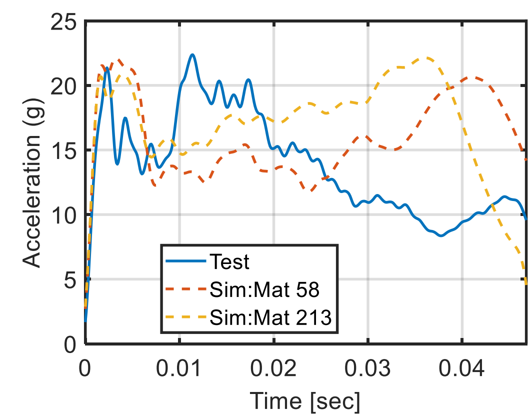


Structural Energy Absorber Results

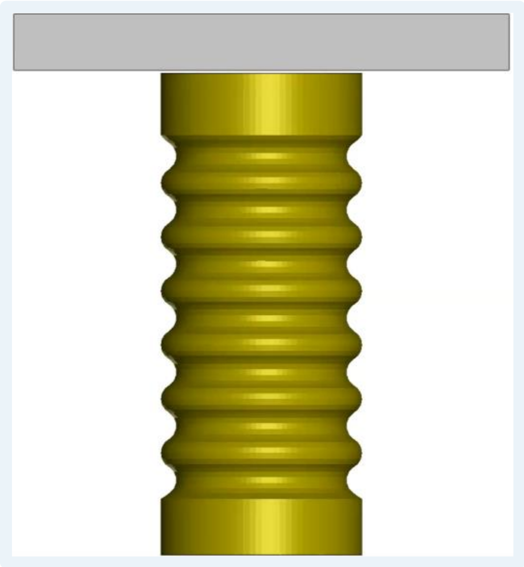
- MAT 213 damage and failure parameters calibrated based on crush tube results.
  - Initially developed MAT 213 damage parameters to correspond to MAT 58 SLIM values but non-optimal results obtained.
  - Recalibration of MAT 213 damage parameters effectively improved correlation – on par with Mat 58 – and improved prediction at initial contact
- Verified calibrated response against subfloor test model
  - Mat 213 model showed similar on par correlation to Mat 58 for the subfloor model

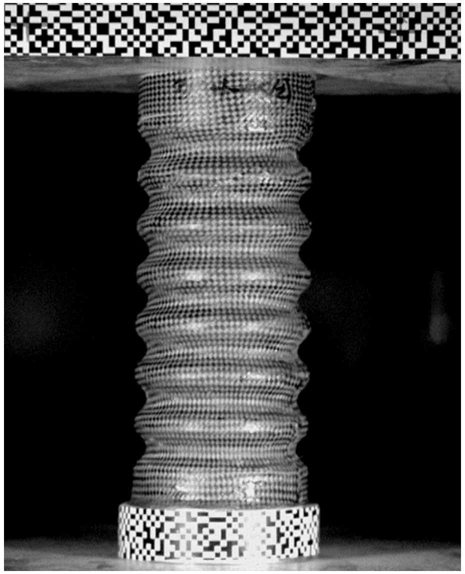




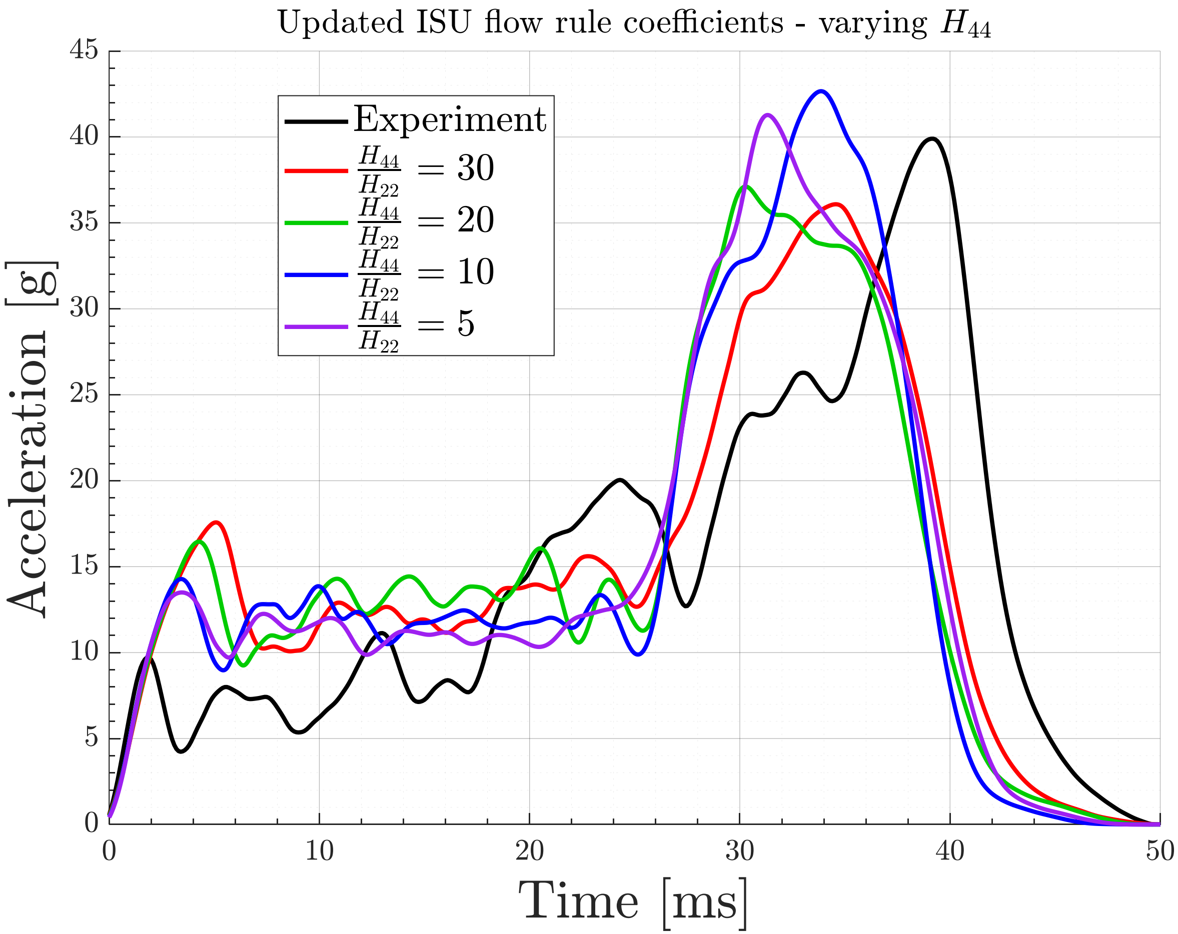


Structural Energy Absorber Modeling





Damage in T1, T2, shear; no post-peak defined for compression

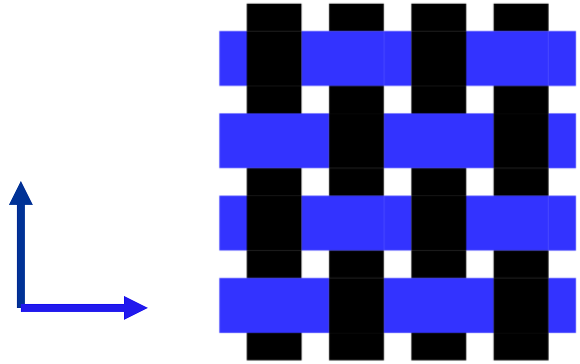


Karen Jackson: $H_{11} = 0.007$, $H_{22} = 0.082$, $H_{12} = -0.00085$, $H_{44} = 3.875$
Updated ISU: $H_{11} = 0.0303$, $H_{22} = 0.23232$, $H_{12} = -0.0808$, $H_{44} = 6.9697$

Bird Strike on Rotorcraft Fuselage Structure

Warp and fill fibers:

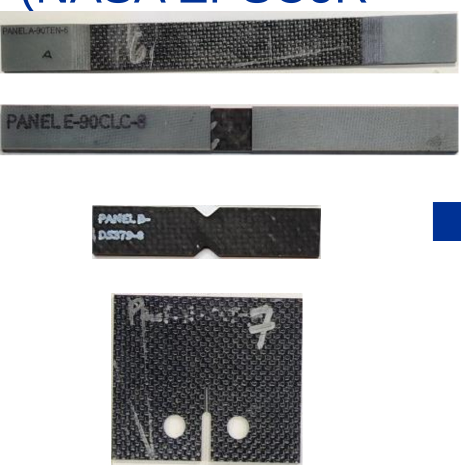
3K70 carbon fiber tows



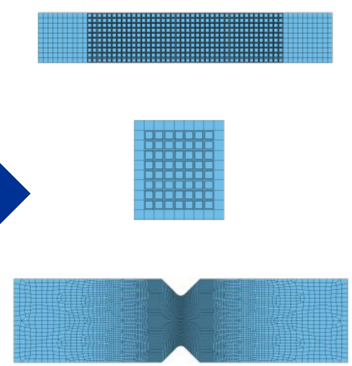
Matrix:

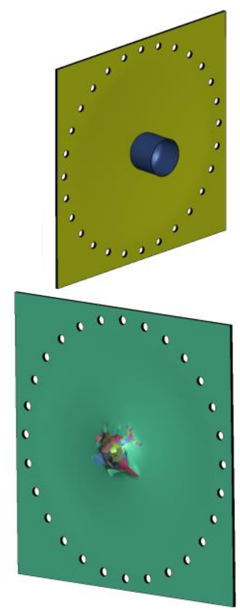
INF 114 epoxy resin (thermoset)

Wichita State University (NASA EPSCoR

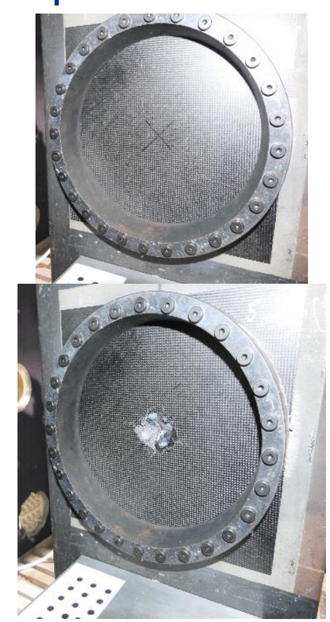


LS-DYNA explicit finite element modeling using *MAT_213





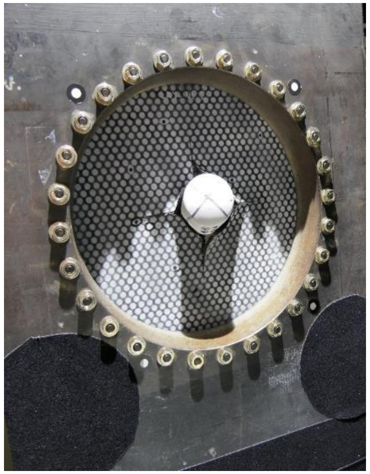
NASA GRC Ballistic Impact Laboratory



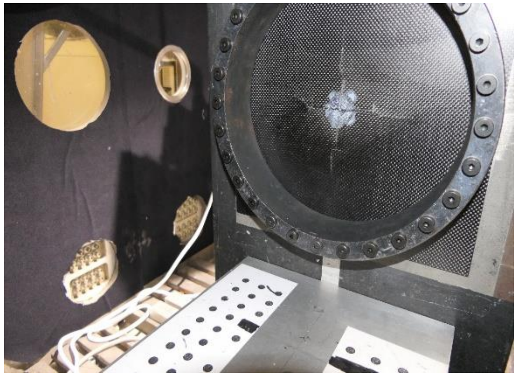
Bird Strike on Rotorcraft Fuselage Structure

Preliminary *MAT_213 characterization from quasi-static coupon-level data

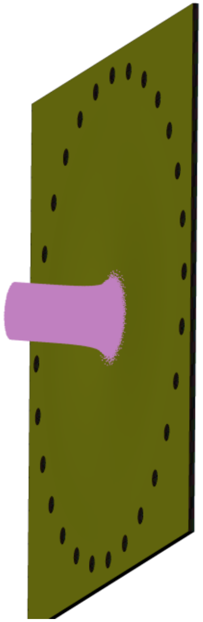
Done by Jacob Putnam at NASA LaRC using data from Wichita State University



Calibrating *MAT_213 constitutive model, tiebreak contacts through modeling coupon tests and HEDI of *<u>aluminum</u>* projectile on composite panels (NASA GRC)



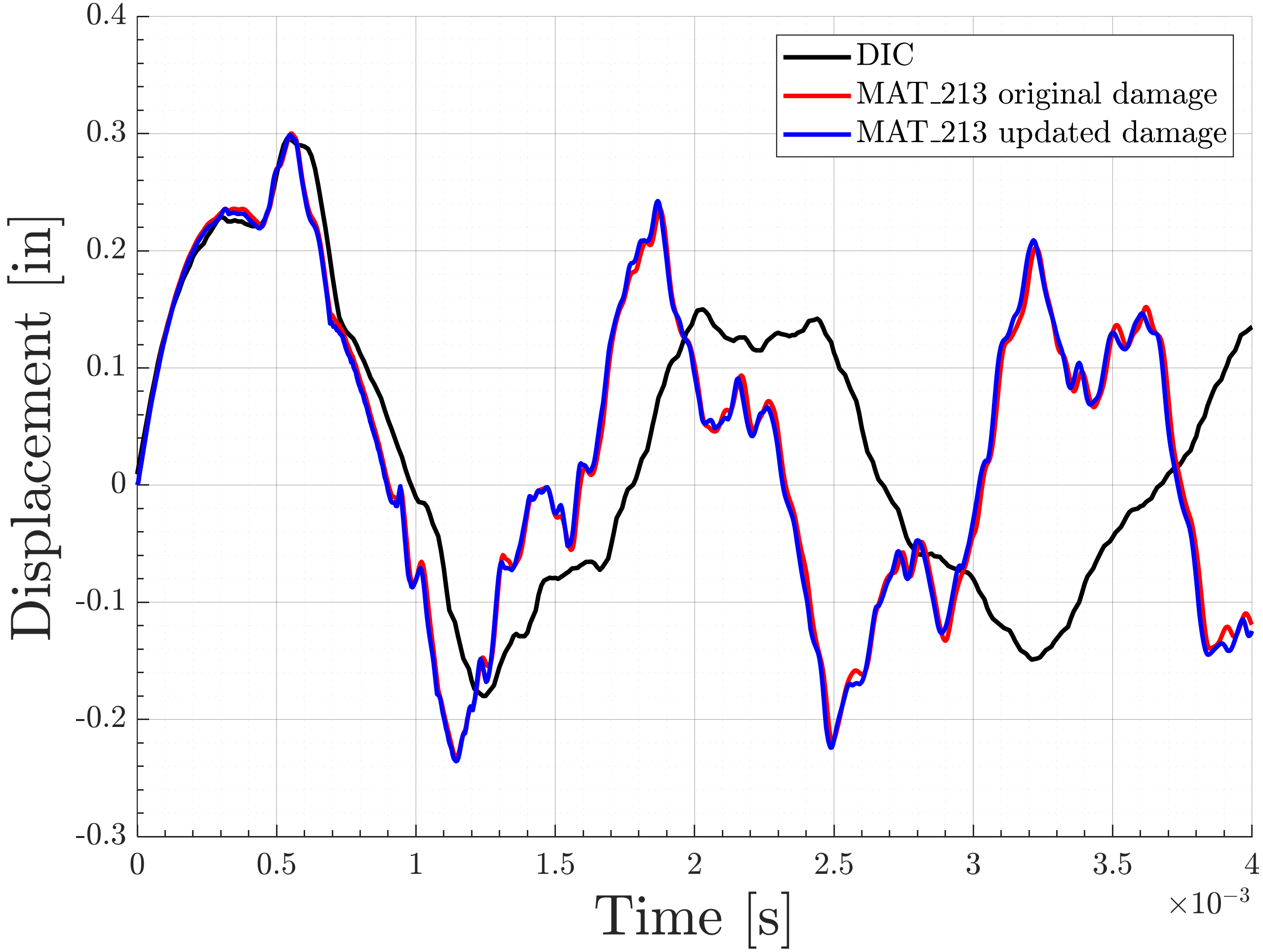
Pre-test prediction of artificial bird strike resistance of composite panels (NASA GRC)



Bird Strike on Rotorcraft Fuselage Structure

Out-of-plane displacement from center of back-side ply

[45/0/-45/90/90/-45/0/45]S



Impact Simulations of Thermoplastic Matrix Composites

- Material: Continuous Fiber IM7/PEKK Thermoplastic
- Ply-by-ply modeling approach with fiber-aligned meshing
  - Inter-ply (delamination): Contact based cohesive zone (tiebreak)
  - Intra-ply behavior using with MAT_213:
    - Flow coefficients calculated assuming plastic Poisson's ratios are equal to elastic
    - Thin shell elements using ELFORM=16

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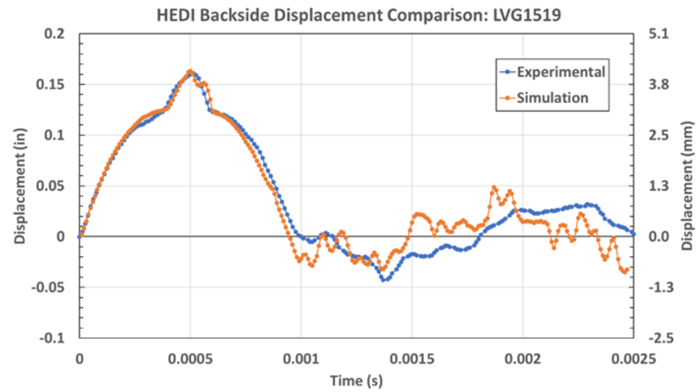
Impact Simulation Results

- Thin shell impact model using tiebreak contact based on Ricks, T. et al. 2023 is enhanced to included fiber-aligned meshing
  - Good agreement between experiment and simulation at low velocities.
  - Delamination at higher velocities underpredicted compared to experiments.
- Ongoing work includes improvements in predicting the simulated penetration threshold and development of solid element impact model



Comparison of the backside displacement at the panel center from the lowest velocity, 18.3 m/s, HEDI experiment with FEA simulation.

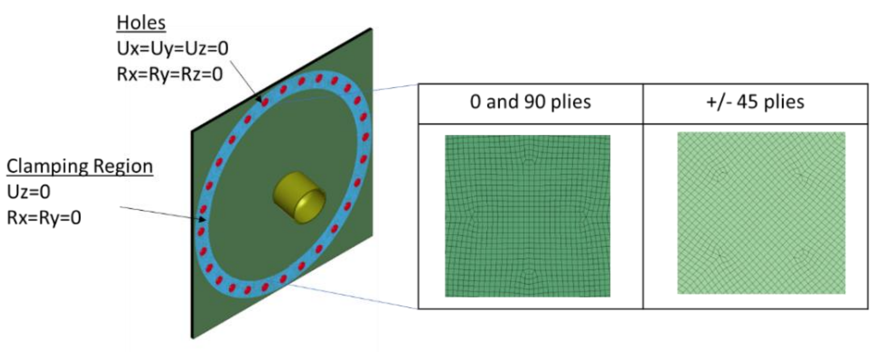
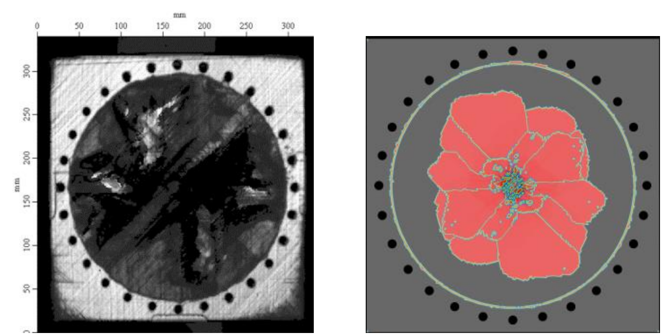


Illustration of fiber aligned meshing and boundary conditions for HEDI simulations.



Comparison of post-test NDE image (left) which shows no damage in gray and damage in black and predicted simulation damage (right) which shows no damage in gray and damage in red for a high velocity, 144.8 m/s, case with large damage but no penetration.

Conclusions and Future Work

- New composite material model MAT 213 has been developed to provide improved predictive capability for LS-DYNA simulations of composite crash, crush and impact.
- Initial results indicate reasonable levels of success in using MAT 213 to simulate impact and crush problems.
- Several areas of future work identified
  - Improved methods of characterizing plasticity parameters and post-peak damage and failure response.
  - Improved methods to simulate interply delamination.
  - Rigorous incorporation of strain rate and temperature effects into MAT 213 simulations.
  - Expanded investigations into various composite impact and crush problems.

Acknowledgements

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- Dr. Ashraf Bastawros-Iowa State University