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Validation of a New Aluminum Honeycomb Crush Model with Dynamic Impact Tests

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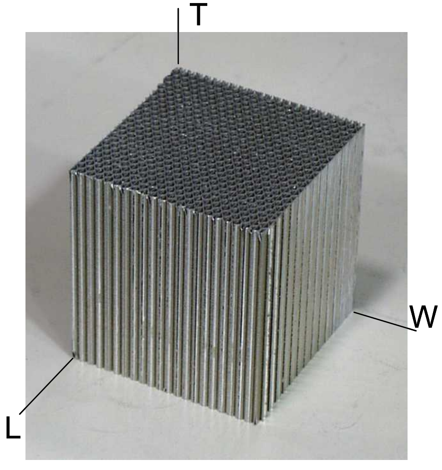
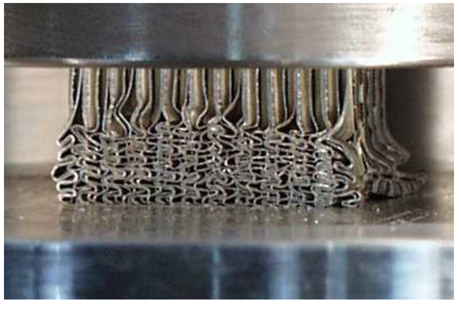
Overview

- Aluminum Honeycomb
- Validation Space
- Honeycomb Crush Model
- Rate Sensitivity
- Validation Procedure
- Results
- Summary

Aluminum Honeycomb



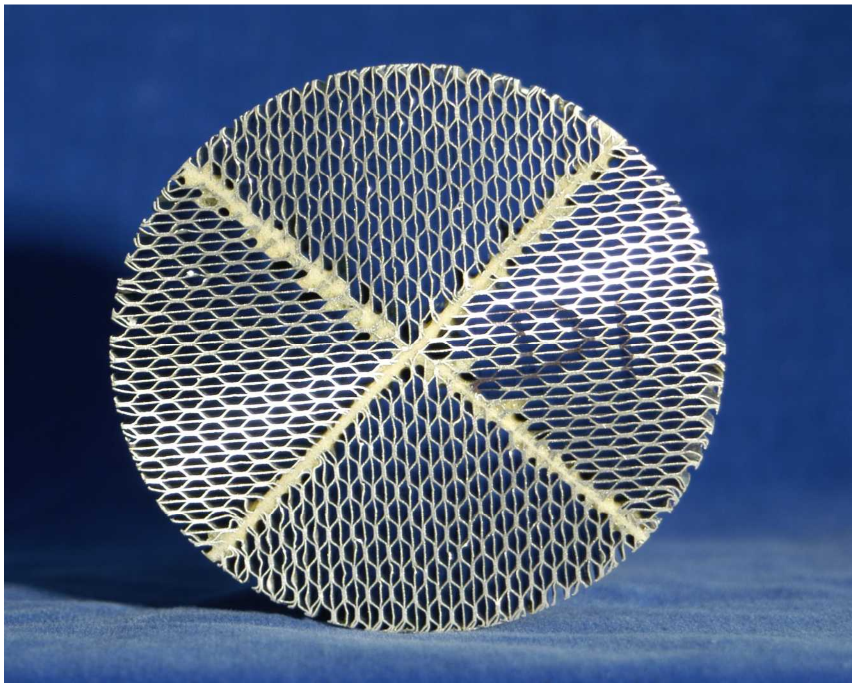


plastic buckling

Ideal crush mode

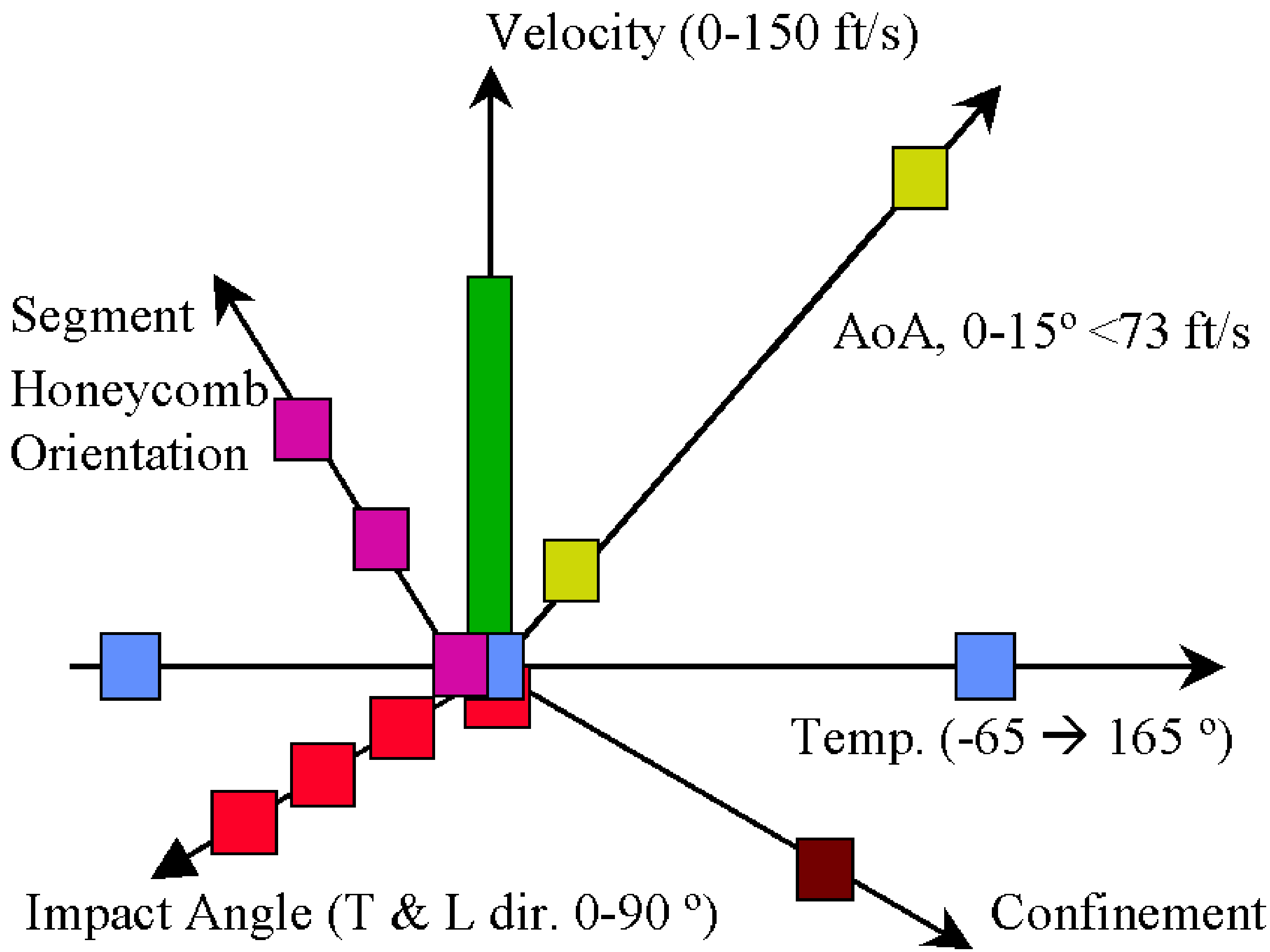
- High density, 38 lb/ft^3
- Strongly orthotropic
  - T-direction is strongest
  - L-direction is intermediate
  - W-direction is weakest
- Orthotropic Crush Model handles on-axis well
  - Ref. Whirley, Engelman, & Halquist
- Honeycomb Crush model demonstrated more predictive for quasi-static biaxial crush experiments

Segmented Honeycomb



- Intermediate strength L-direction is approximately radial
- Weak W-direction is oriented approximately in the tangential direction
- Epoxy used to bond segments together – adds small amount of crush strength
- Constrains honeycomb to localized (high energy absorbing) buckling pattern

Validation Space



Honeycomb Crush Model

- 6 Yield functions with original OCM terms in red boxes
- New Yield surface includes transverse stress influence
- Hardening function includes:
  - rate term
  - cross-axis coupling in normal strains
  - shear strain dependence
- Random variables: TS, LS, WS, TLS, LWS, and WTS

$$\Psi_T = \left| a_1 \boxed{\sigma_{TT}} + b_1 \sigma_{LL} + c_1 \sigma_{WW} \right| - \boxed{TS * H_T(e_{vol})} * G(rate) * TTP(e_{tt}) * TLP(e_{ll}) * TWP(e_{ww})$$

$$\Psi_L = \left| a_2 \sigma_{TT} + b_2 \boxed{\sigma_{LL}} + c_2 \sigma_{WW} \right| - \boxed{LS * H_L(e_{vol})} * G(rate) * LTP(e_{tt}) * LLP(e_{ll}) * LWP(e_{ww})$$

$$\Psi_W = \left| a_3 \sigma_{TT} + b_3 \sigma_{LL} + c_3 \boxed{\sigma_{WW}} \right| - \boxed{WS * H_W(e_{vol})} * G(rate) * WTP(e_{tt}) * WLP(e_{ll}) * WWP(e_{ww})$$

$$\Psi_{TL} = \boxed{\left| \sigma_{TL} \right| - TLS * H_{TL}(e_{vol})} * G(rate) * TLTLP(e_{tl})$$

$$\Psi_{LW} = \boxed{\left| \sigma_{LW} \right| - LWS * H_{LW}(e_{vol})} * G(rate) * LWLWP(e_{lw})$$

$$\Psi_{WT} = \boxed{\left| \sigma_{WT} \right| - WTS * H_{WT}(e_{vol})} * G(rate) * WTWTP(e_{wt})$$

OCM reference: Whirley, R.G., Engelman, B.E., and Hallquist, J.O., 1991, "DYNA3D Users Manual," Lawrence Livermore Laboratory, Livermore, CA.

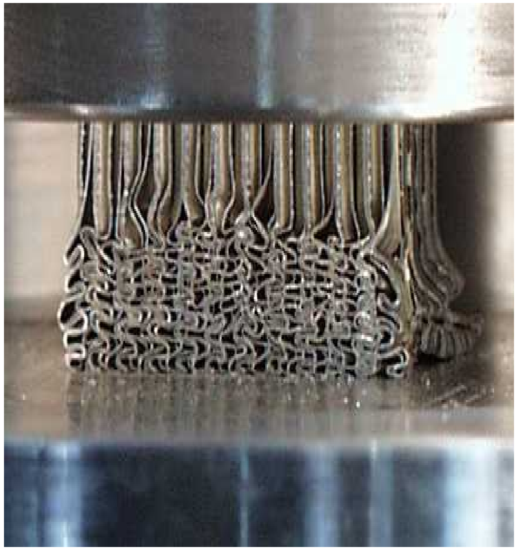
HCM Parameter Uncertainty Quantification

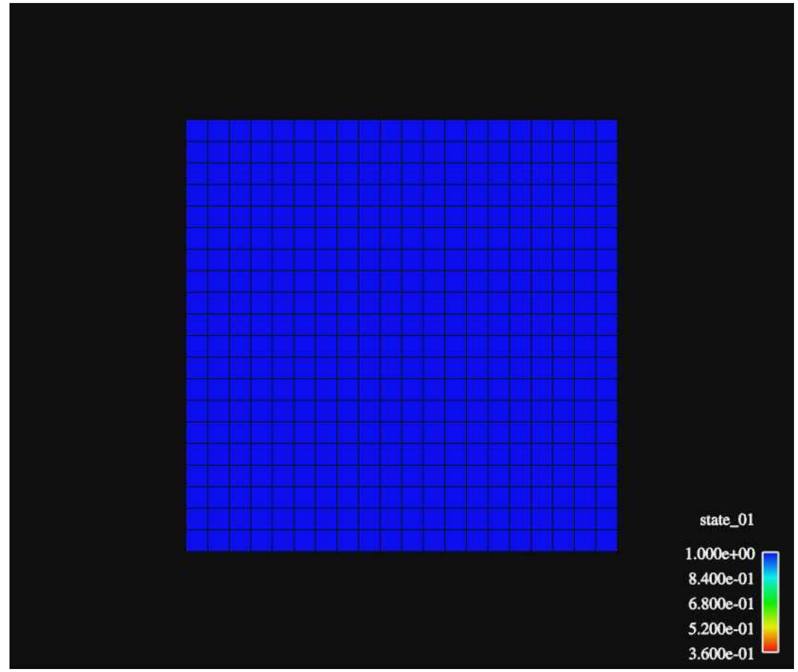
Parameter	Value	Description of Parameter
TS (psi)	6100 +/- 10%	Initial strength parameter for TT yield surface
LS (psi)	946.7+/- 10%	Initial strength parameter for LL yield surface
WS (psi)	600+/-10%	Initial strength parameter for WW yield surface
TLS (psi)	1200 to 1800	Initial strength parameter for TL yield surface
LWS (psi)	300 to 675	Initial strength parameter for LW yield surface
WTS (psi)	700 to 1100	Initial strength parameter for WT yield surface
Friction	0.2 to 1.0	Coulomb friction values

Random Variables to be propagated through the HC Model

- Normal Crush Strengths: TS, LS, WS
  - Upper bound: mean plus 10%
  - Lower bound: mean minus 10%
- Shear Strengths: TLS, WTS, LWS
  - Greatest amount of uncertainty, +/- 30%
- Friction
  - Shear deformation is coupled with friction

Continuum vs Structural Behavior





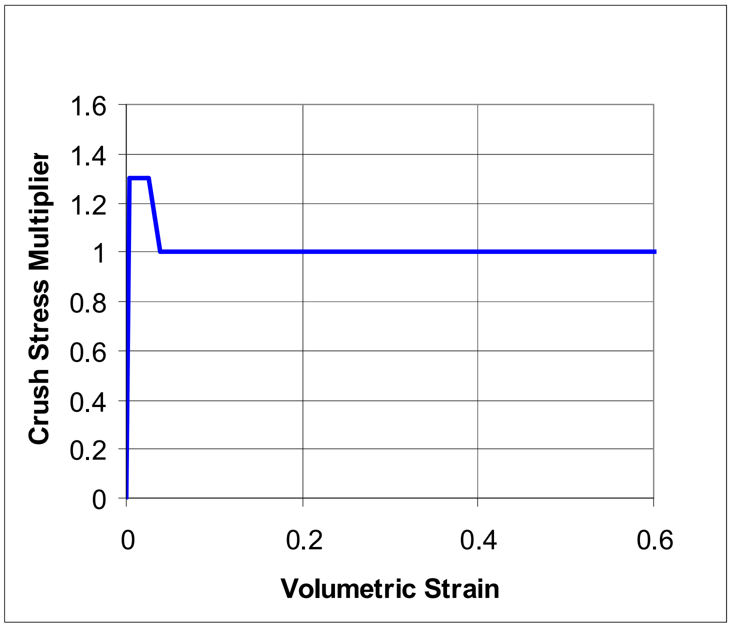
Characteristic length: physics of honeycomb show that localized buckles form with a length of approximately the unit cell size, 0.125”

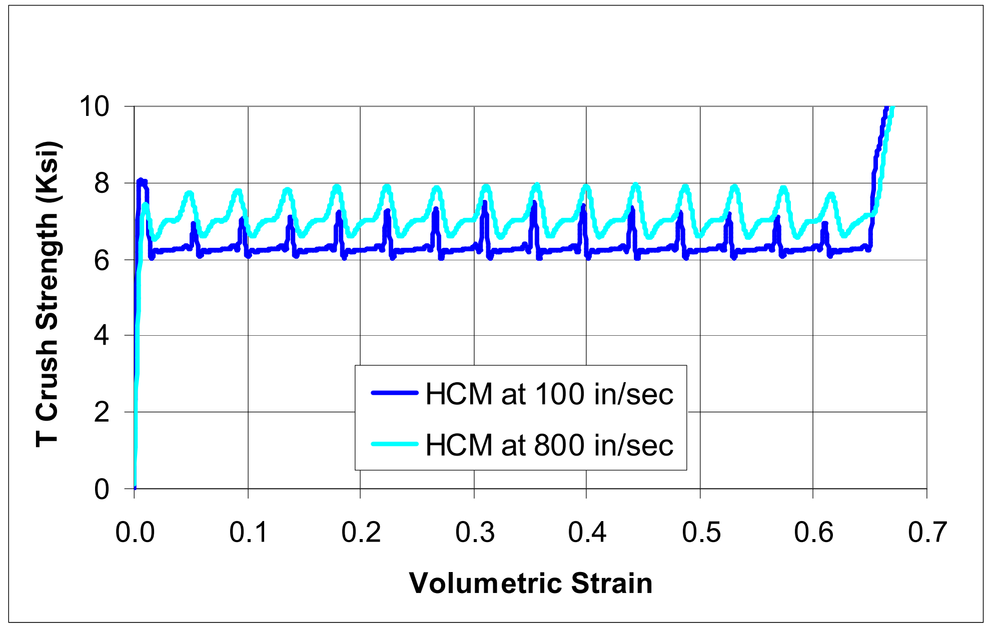
FE model is given similar mesh size to build in characteristic length

TTP tabular function defined with initial peak of 1.3 x crush strength

Continuum vs Structural Behavior Initial Peak Stress

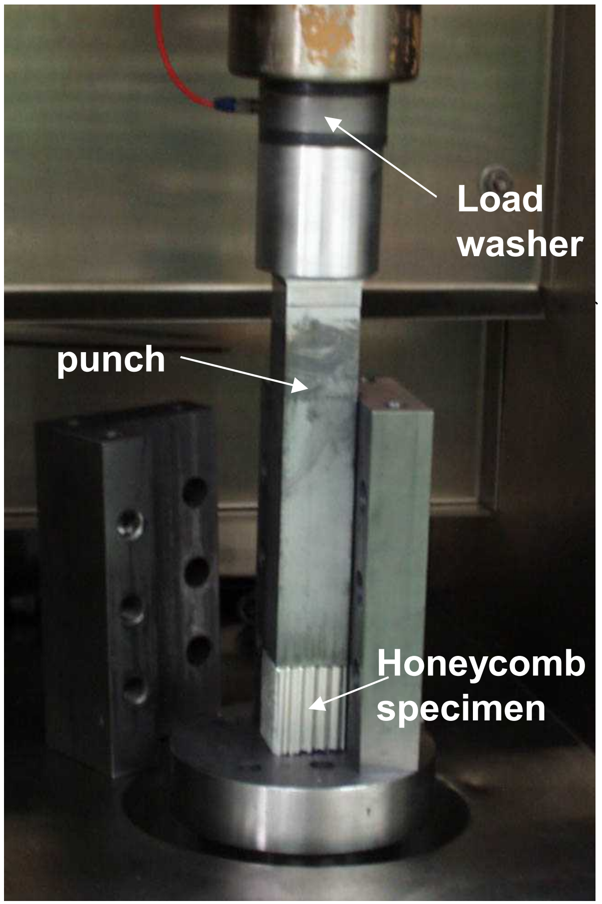
TTP function part of Yield Surface in the strong T-direction generates rate sensitivity

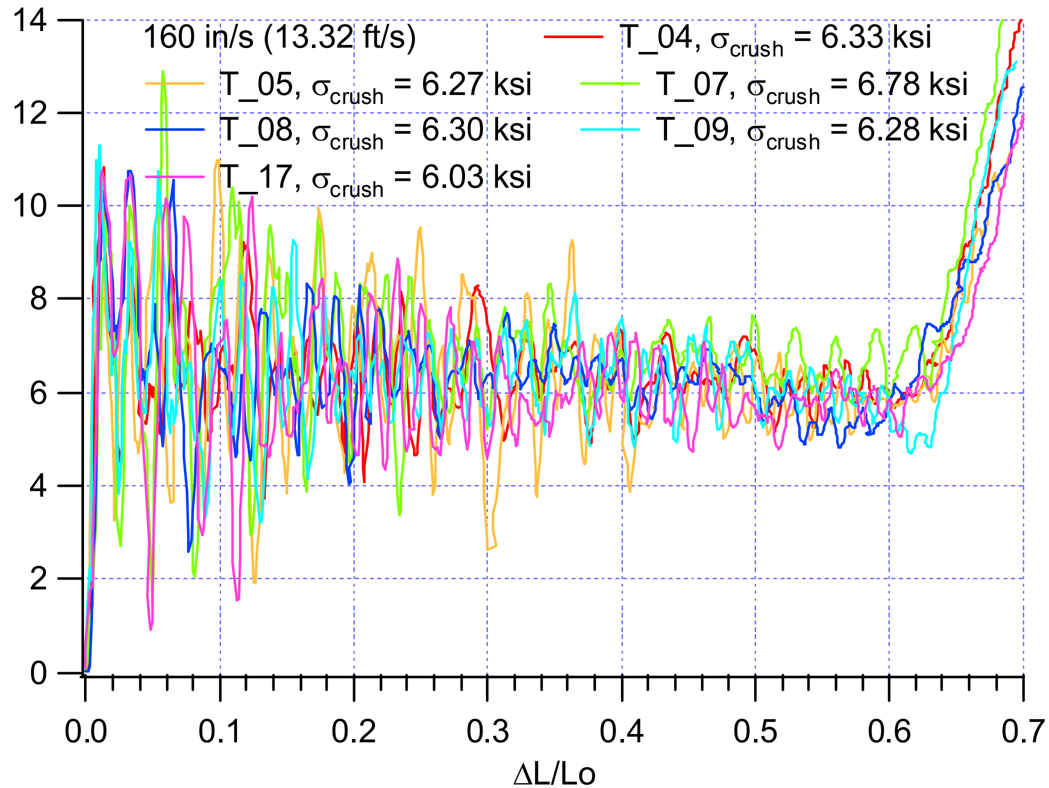




Programming initial peak into TTP Function makes each element effectively go through a virtual load up and localized buckle type of process.

Dynamic Crush Technique #1



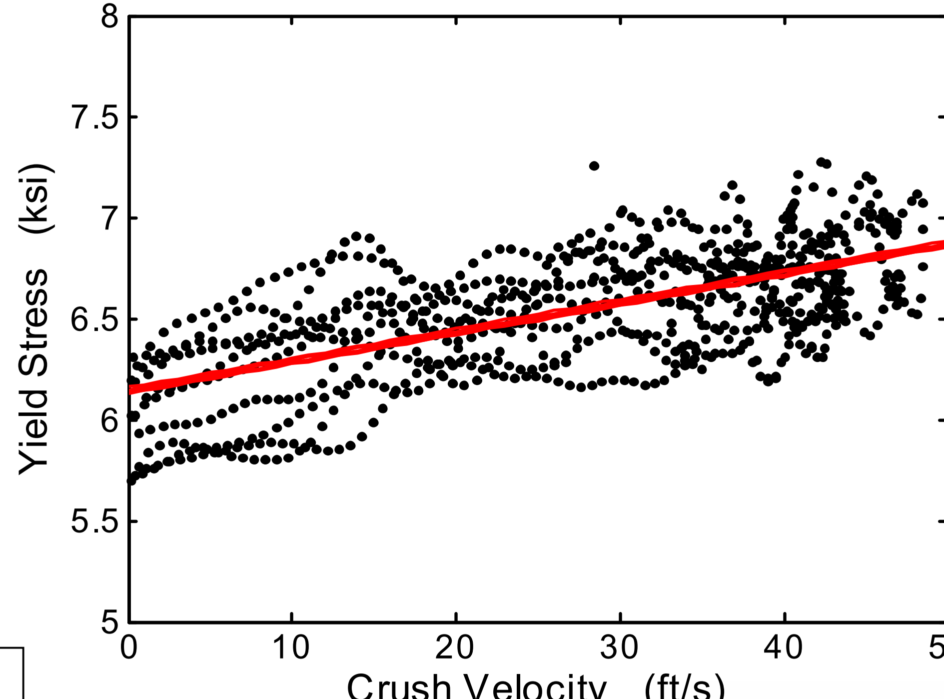


MTS confined compression tests with crush velocities of 160 in/sec.

Dynamic Crush Technique #2
Drop Table Tests

Honeycomb sample

$$\sigma_{crush} = 6.1 + 1.45 * 10^{-2}\left(V_{crush}\right)$$



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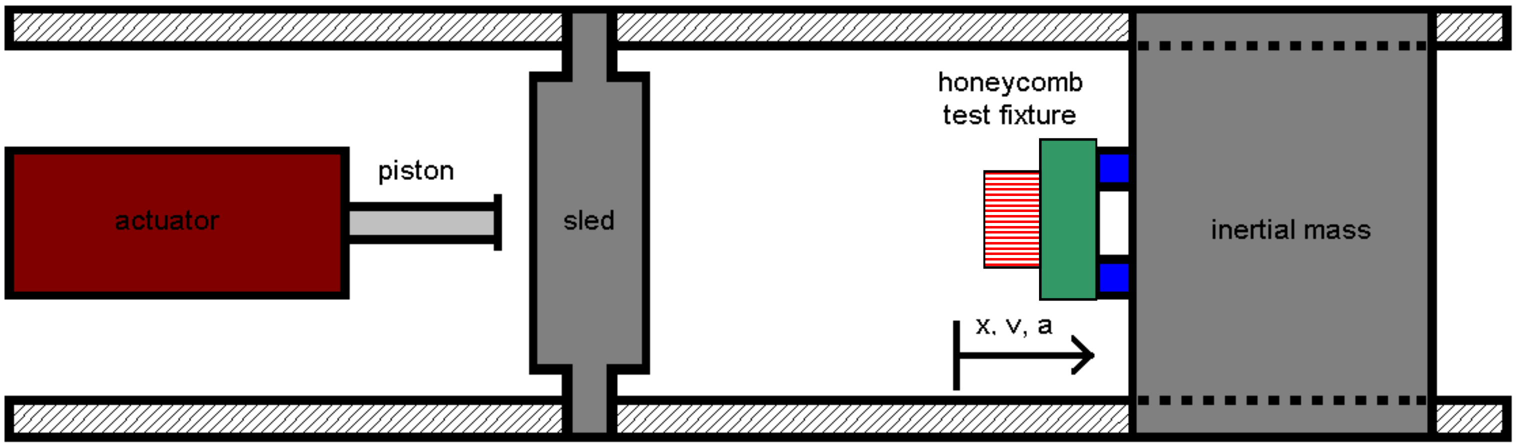
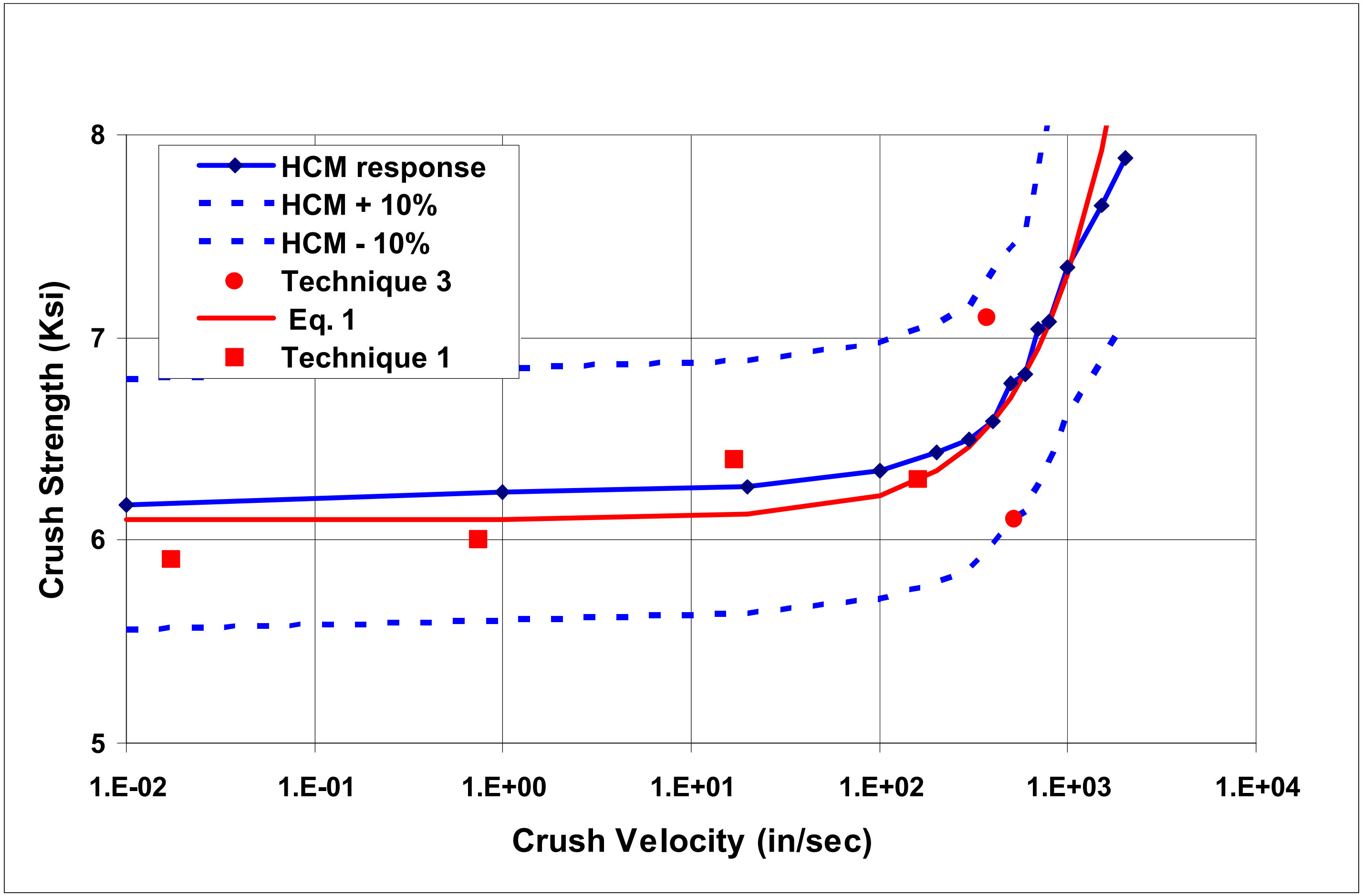
Dynamic Crush Technique #3
Compressed Gas Driven Actuator



Sandia Horizontal Actuator Testing Results		
Sample Name	Mean Crush Rate (ksi)	Mean Crush Stress (Ksi)
V4	377	7.1
V5	517	6.1

Combined Dynamic Crush Test Data vs. HC Model Fit



Material variability was far greater than the experimental accuracy.

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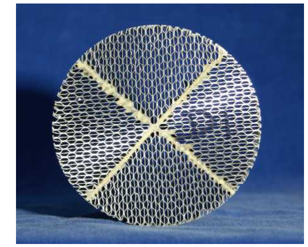
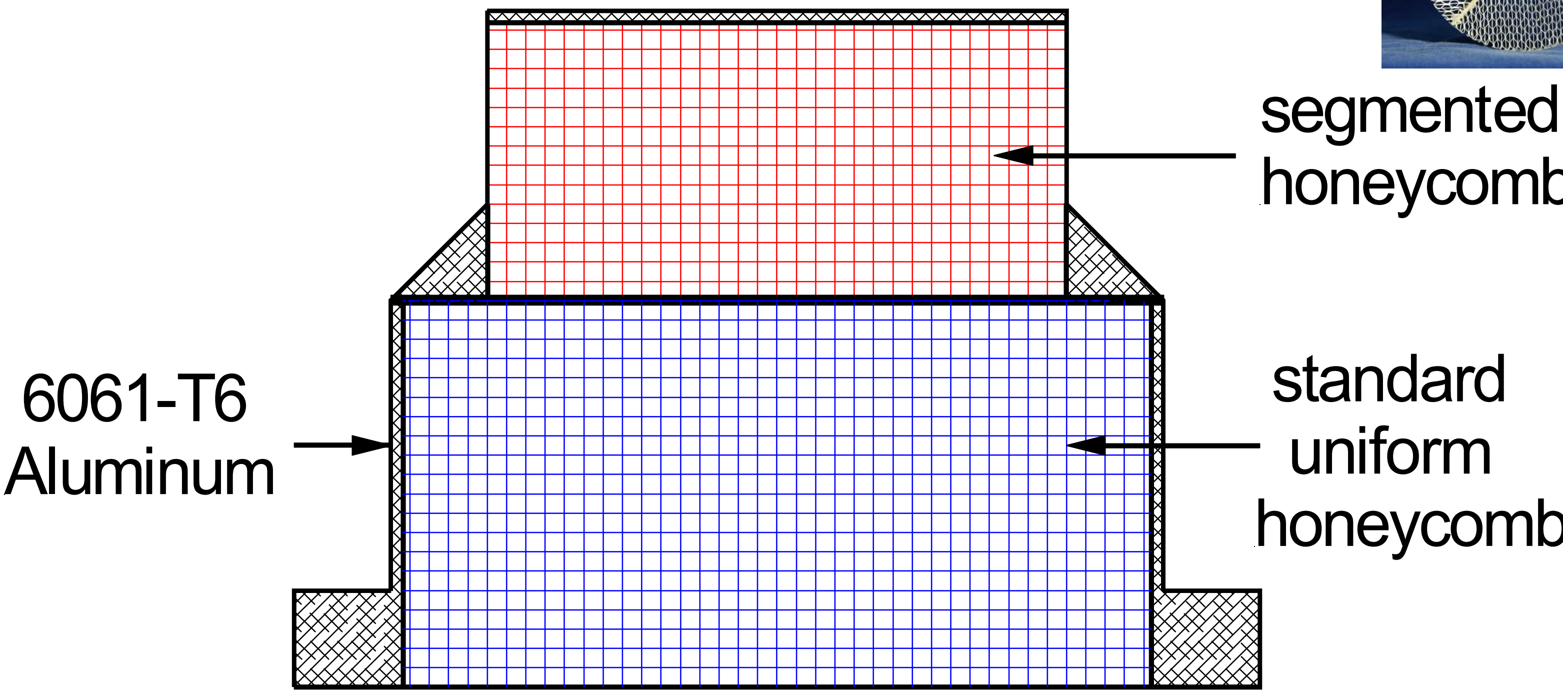
Validation Test Article

Axisymmetric structure





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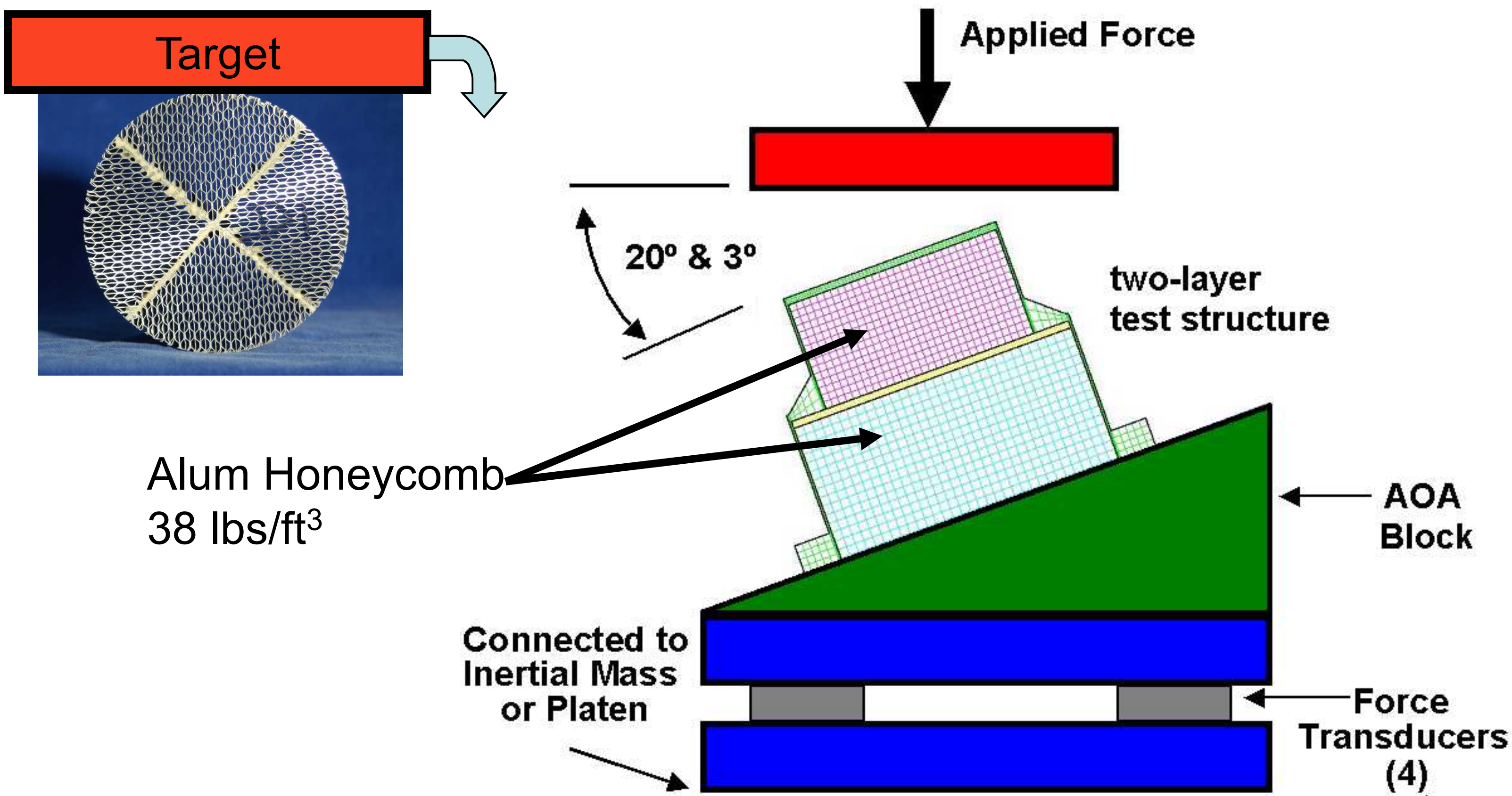
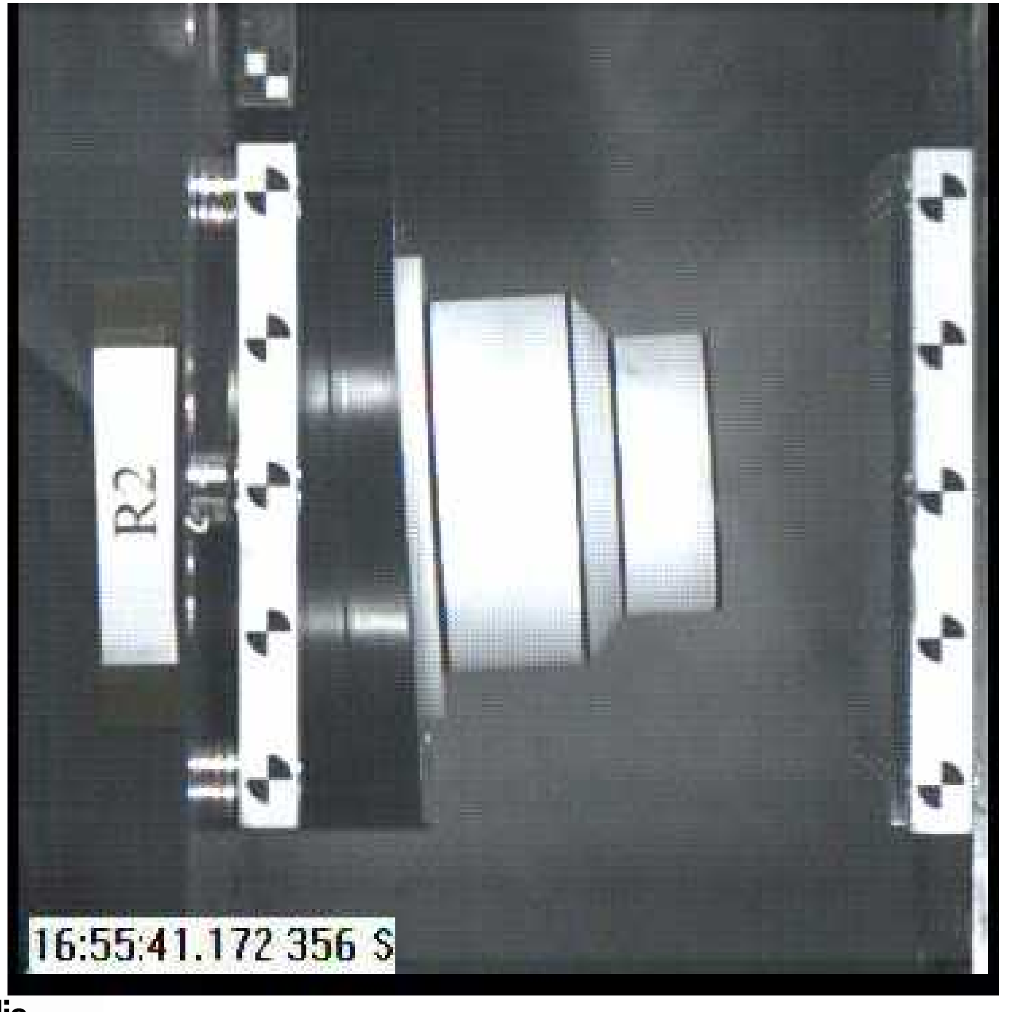
Validation Experiment
Two-layer energy absorber structure
(quasi-static up to 85 ft/sec)



Validation Test Matrix

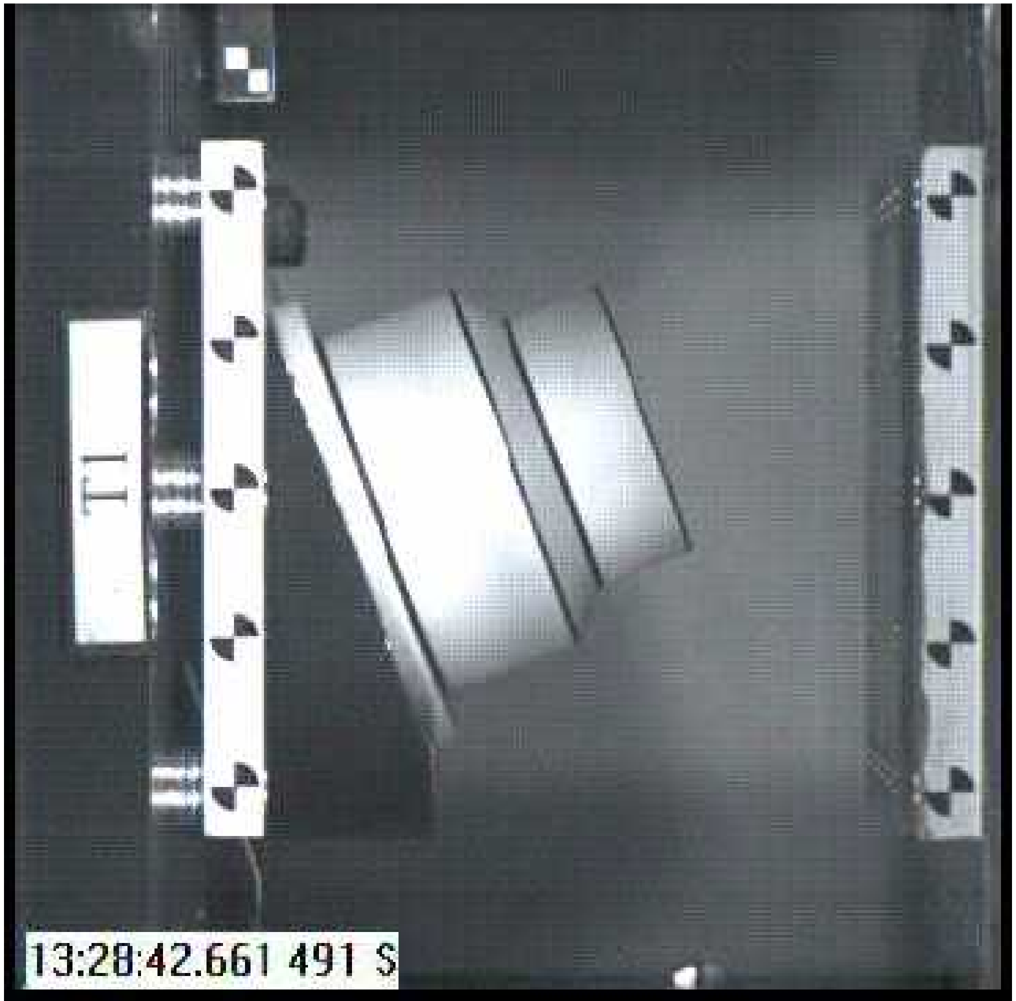
Quasi-static Test Matrix ~ 0 ft/sec			
Configuration	Temperature deg F	Units	Test Names
3^o empty can	T_o	3	G1, 2, 3
20^o empty can	T_o	3	H1, 2, 3
3^o X on L	T_o	3	J1, 2, 3
20^o X on L	T_o	3	K1, 2, 3
20^o + on L	T_o	3	L1, 2, 3
20^o + on L	165^o	3	M1, 2, 3
3^o X on L	165^o	3	W1, 2, 3
Dynamic Test Matrix ~60-85 ft/sec			
3^o X on L	T_o	3	R1, 2, 3
3^o X on L	165^o	3	S1, 2, 3
20^o X on L	T_o	3	T1, 2, 3
20^o X on L	165^o	3	U1, 2, 3

Validation Experiment
3 Degree Angle-of-Attack (movie)



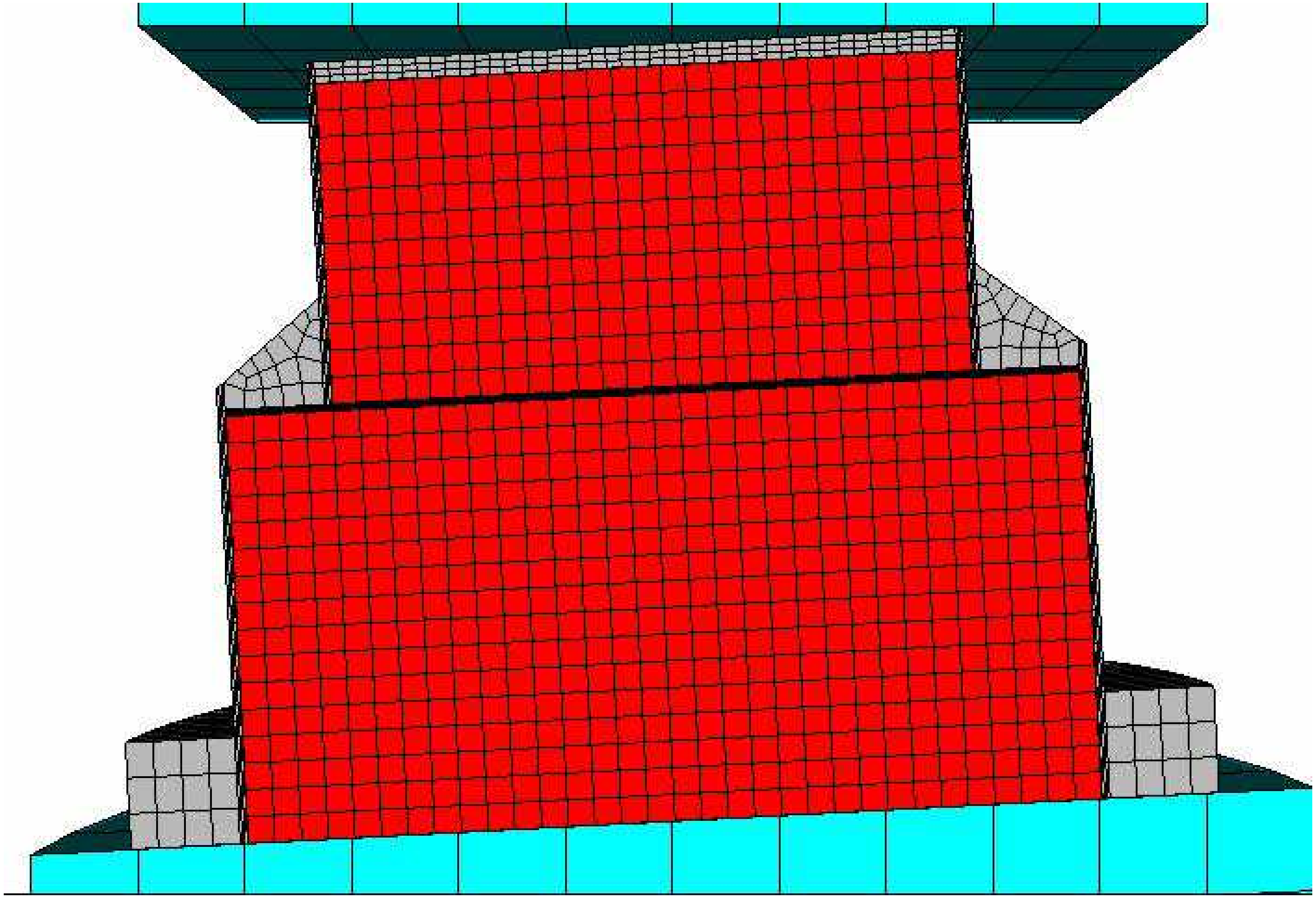
85 ft/sec impact velocity

Validation Experiment
20 Degree Angle-of-Attack (movie)



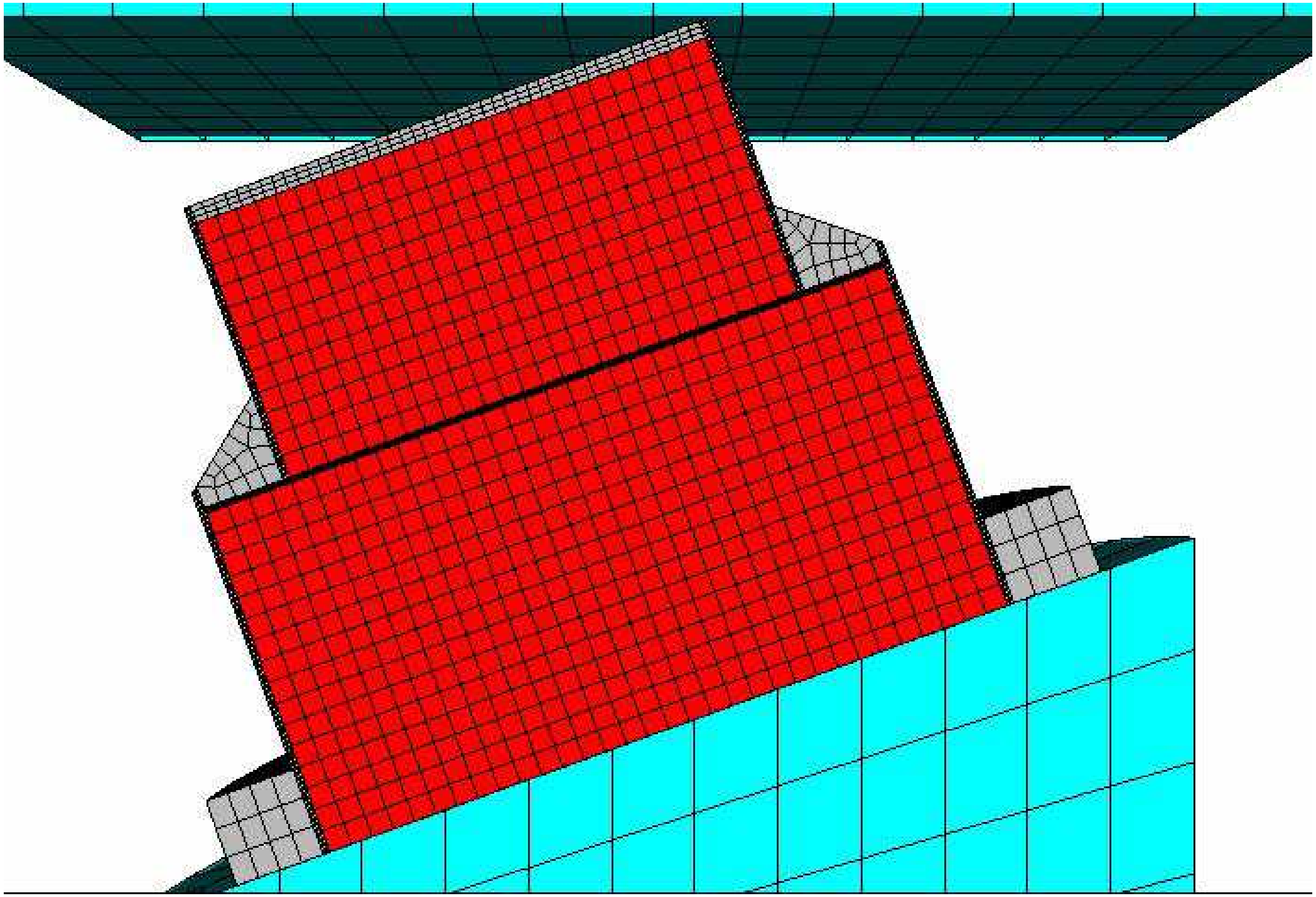
68 ft/sec impact velocity

Presto/HCM Model Prediction 3 degree angle-of-attack (animation)



85 ft/sec Impact velocity

Presto/HCM Model Prediction 20 degree Angle-of-Attack (animation)



68 ft/sec impact Velocity, high friction

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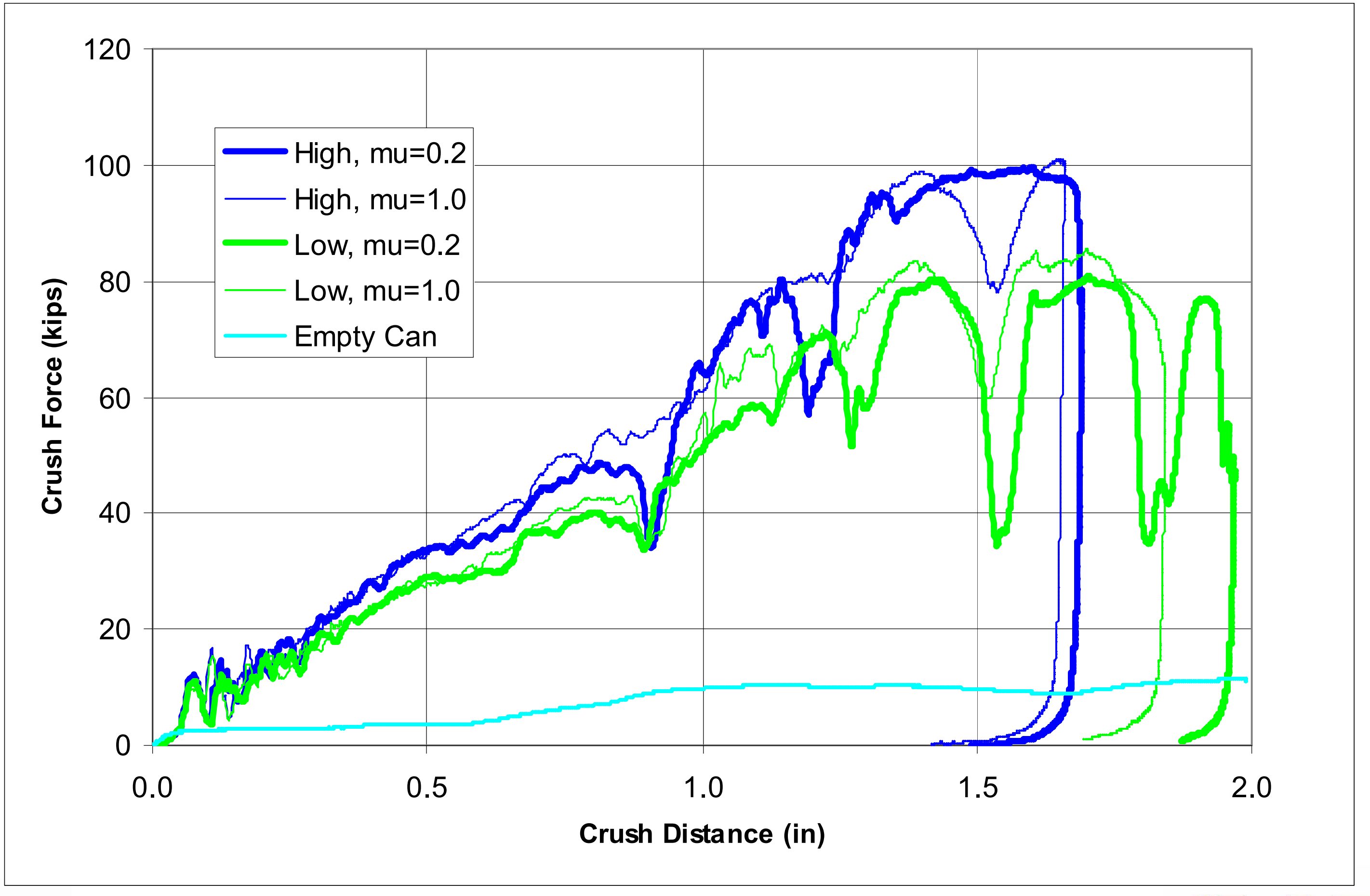
Presto/HCM Model predictions 20 deg AoA



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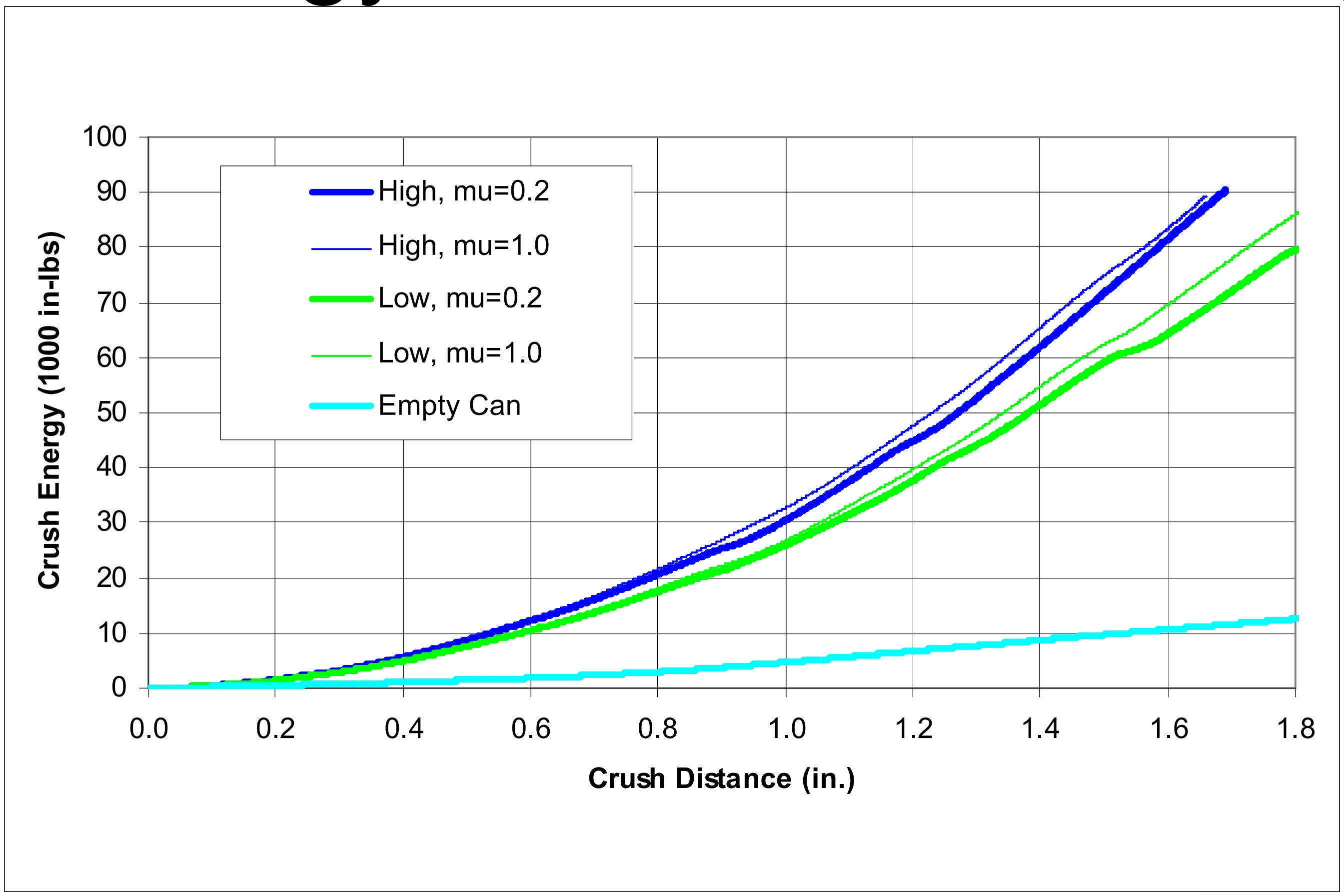
Presto/HCM predictions of energy absorbed for 20 deg AoA



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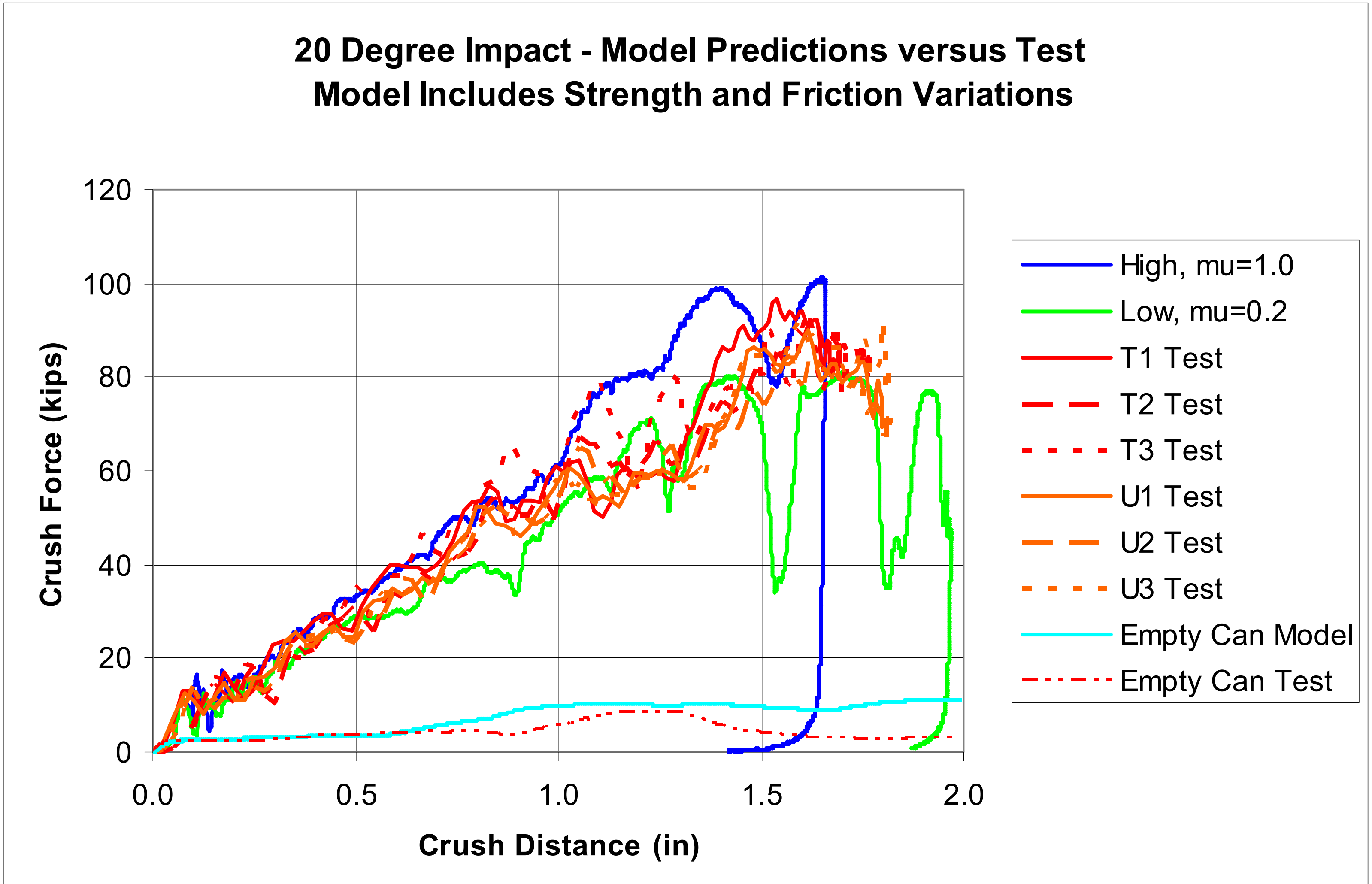
Presto/HCM predictions vs. Test



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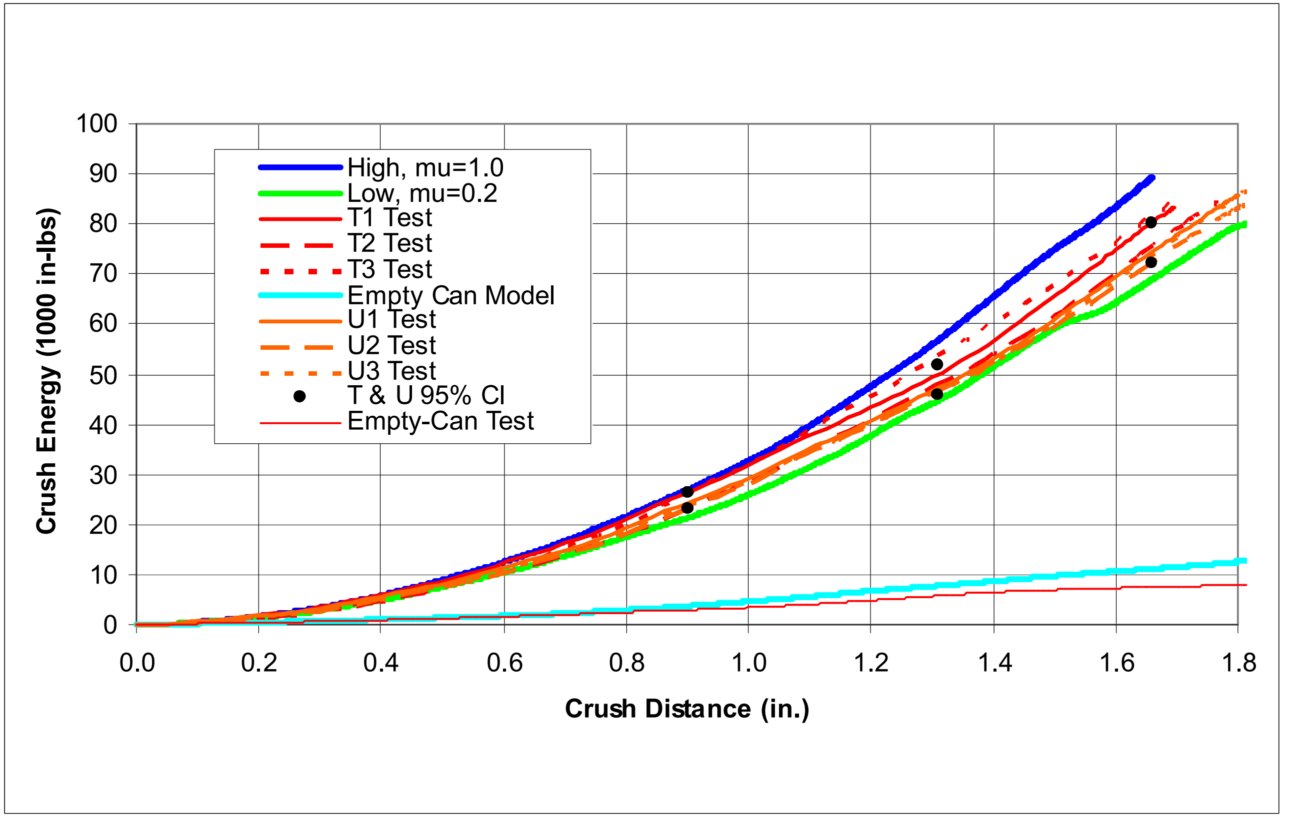
Presto/HCM Model predictions vs. Test with Energy based criterion



Model predictions envelope 95% confidence interval of test data

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Validation Results

3° AOA Impact Model Validation, 95% Confidence Intervals			
	1/3 E	2/3 E	3/3 E
Crush Distance (in)	0.78	1.28	1.73
Eq. 3, Test 95% C. I., 1000 in-lbs	41.1 to 46.1	78.0 to 85.8	114.1 to 126.7
Nominal Model Value, 1000 in-lbs	38.2	80.2	121.6
Eq. 6, Model Error Estimate, 1000 in-lbs	-7.9 to -2.9	-5.7 to 2.1	-5.1 to 7.5
Eq. 6, Model Error Estimate, %	-18.0 to -6.6	-7.0 to 2.6	-4.3 to 6.2

20° AOA Impact Model Validation, 95% Confidence Intervals			
	1/3 E	2/3 E	3/3 E
Crush Distance (in)	0.9	1.31	1.66
Eq. 3, Test 95% C. I., 1000 in-lbs	22.9 to 26.6	45.1 to 52.4	70.9 to 81.2
Nominal Model Value, 1000 in-lbs	24.8	51	79
Eq. 6, Model Error Estimate, 1000 in-lbs	-1.8 to 1.8	-1.4 to 5.8	-2.2 to 8.1
Eq. 6, Model Error Estimate, %	-7.2 to 7.45	-2.9 to 11.9	-2.9 to 10.7

The nominal or average model prediction falls within the 95% CI of the test data mean for 5 out 6 cases. Therefore, the model is judged to be adequately predictive and valid subject to the indicated model uncertainties.

Summary

- The Honeycomb Crush Model has been validated for 38 pcf aluminum honeycomb using an energy based performance criterion
  - Rate sensitivity was accounted for
  - Orthotropic crush parameters and friction uncertainties were propagated through the model
  - Dynamic crush of two stage energy absorber used for the validation experiment
  - Crush velocities up to 85 ft/sec
  - Crush angle-of-attack was 3 deg and 20 deg

Backup Slides

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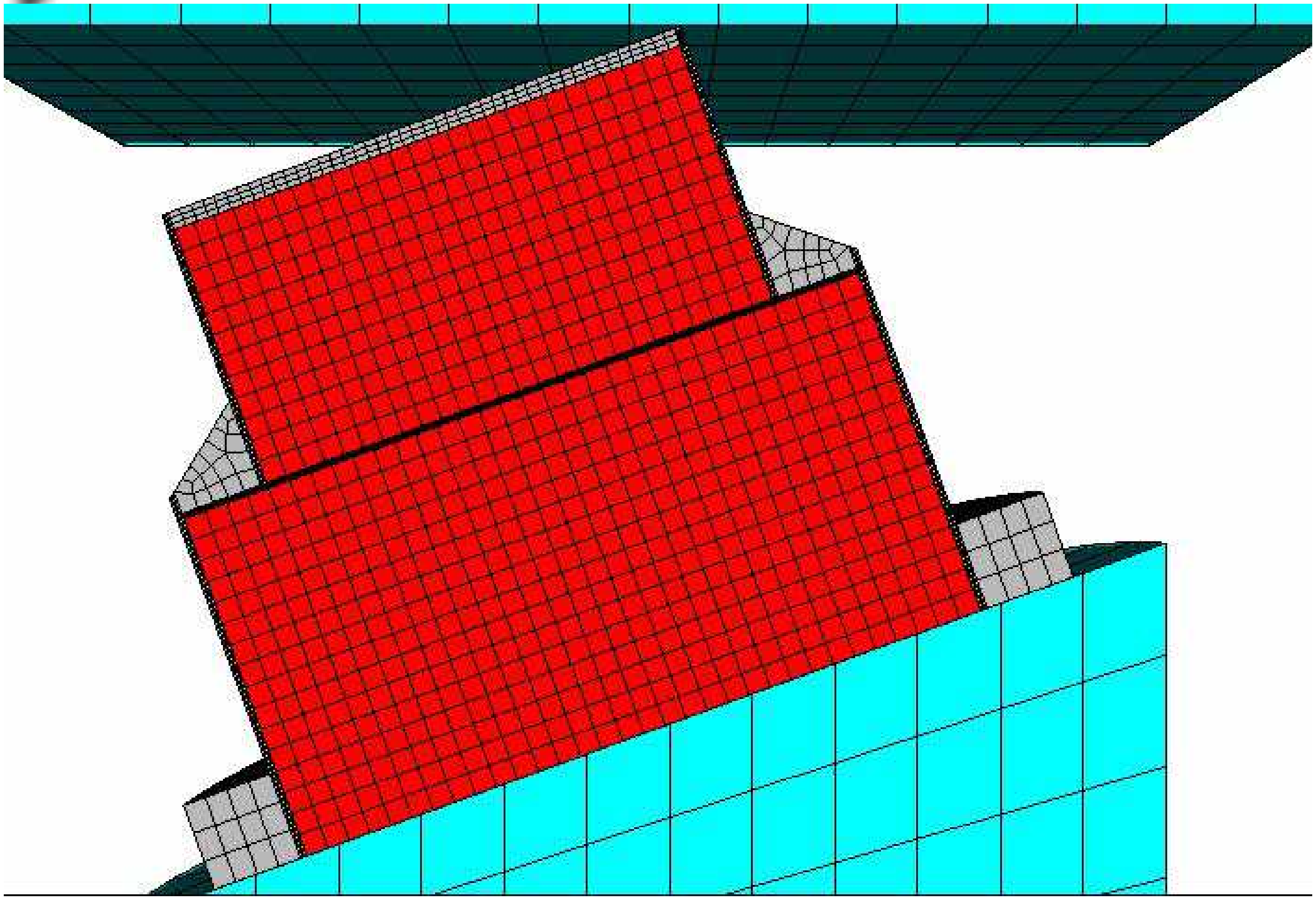
Presto/HCM Model Prediction 20 degree Angle-of-Attack (animation)



68 ft/sec impact velocity,

Low friction

Honeycomb Crush Model

- Complete Orthotropic Elasticity
  - OCM model had only diagonal terms

$$
\begin{Bmatrix} \sigma_{tt} \\ \sigma_{ll} \\ \sigma_{ww} \\ \sigma_{tl} \\ \sigma_{lw} \\ \sigma_{wt} \end{Bmatrix} = \begin{bmatrix} E_{tttt} & E_{ttll} & E_{ttww} & & & \\ E_{ttll} & E_{llll} & E_{llww} & & 0 & \\ E_{ttww} & E_{llww} & E_{wwww} & & & \\ & & & E_{tltl} & & \\ & 0 & & & E_{lwlw} & \\ & & & & & E_{wtwt} \end{bmatrix} \begin{Bmatrix} \varepsilon_{tt} \\ \varepsilon_{ll} \\ \varepsilon_{ww} \\ \varepsilon_{tl} \\ \varepsilon_{lw} \\ \varepsilon_{wt} \end{Bmatrix}
$$

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Honeycomb Crush Model
Cross axis coupling terms

- Cross axis coupling terms, e.g. TLP influences the T-direction due to compaction in the transverse L-direction
- Denominator conserves crush resistance as x-section reduces
- Numerator provides additional hardening as needed

$$TLP(ell) = (1 - E_{STL} * e_{ll})/(1 + e_{ll})$$

$$TWP(eww) = (1 - E_{STW} * e_{ww})/(1 + e_{ww})$$

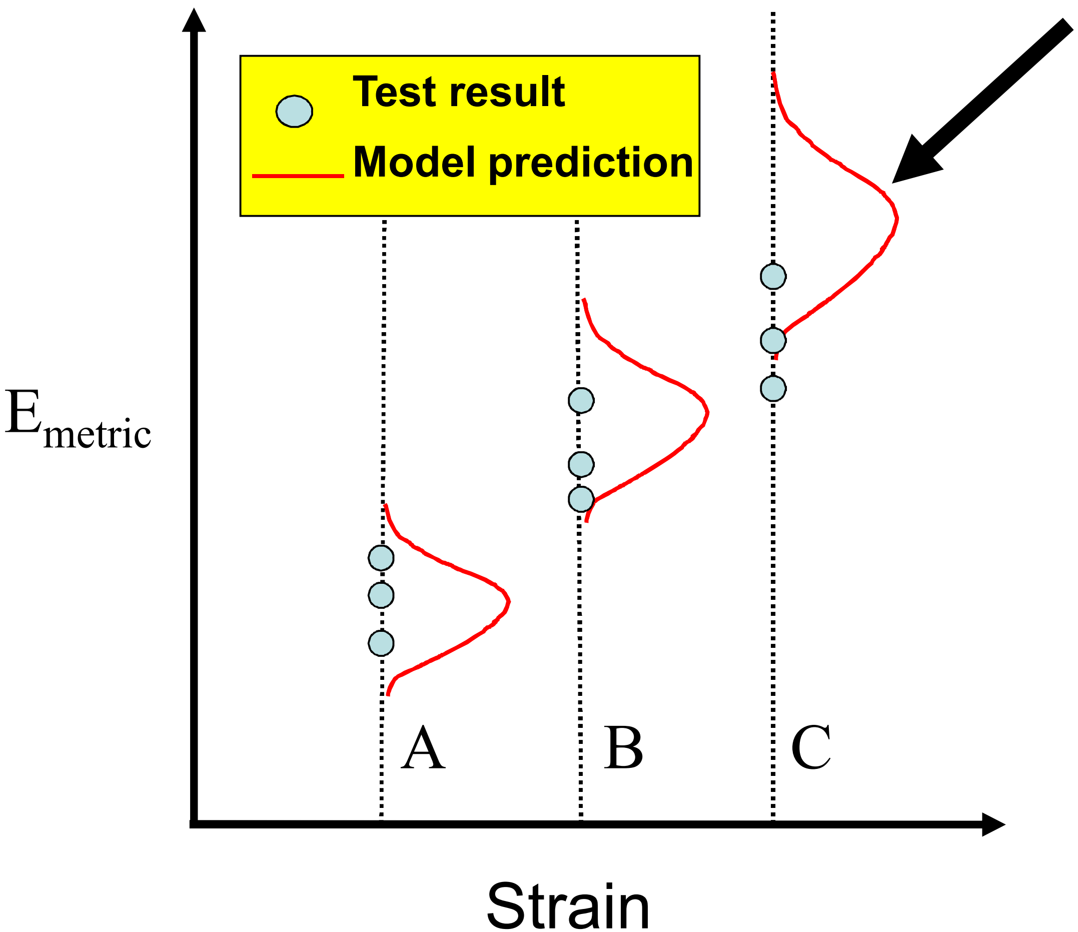
$$LTP(ett) = (1 - E_{SLT} * e_{tt})/(1 + e_{tt})$$

$$LWP(eww) = (1 - E_{SLW} * e_{ww})/(1 + e_{ww})$$

$$WTP(ett) = (1 - E_{SWT} * e_{tt})/(1 + e_{tt})$$

$$WLP(ell) = (1 - E_{SWL} * e_{ll})/(1 + e_{ll})$$

Statistical Assessment of Model Adequacy



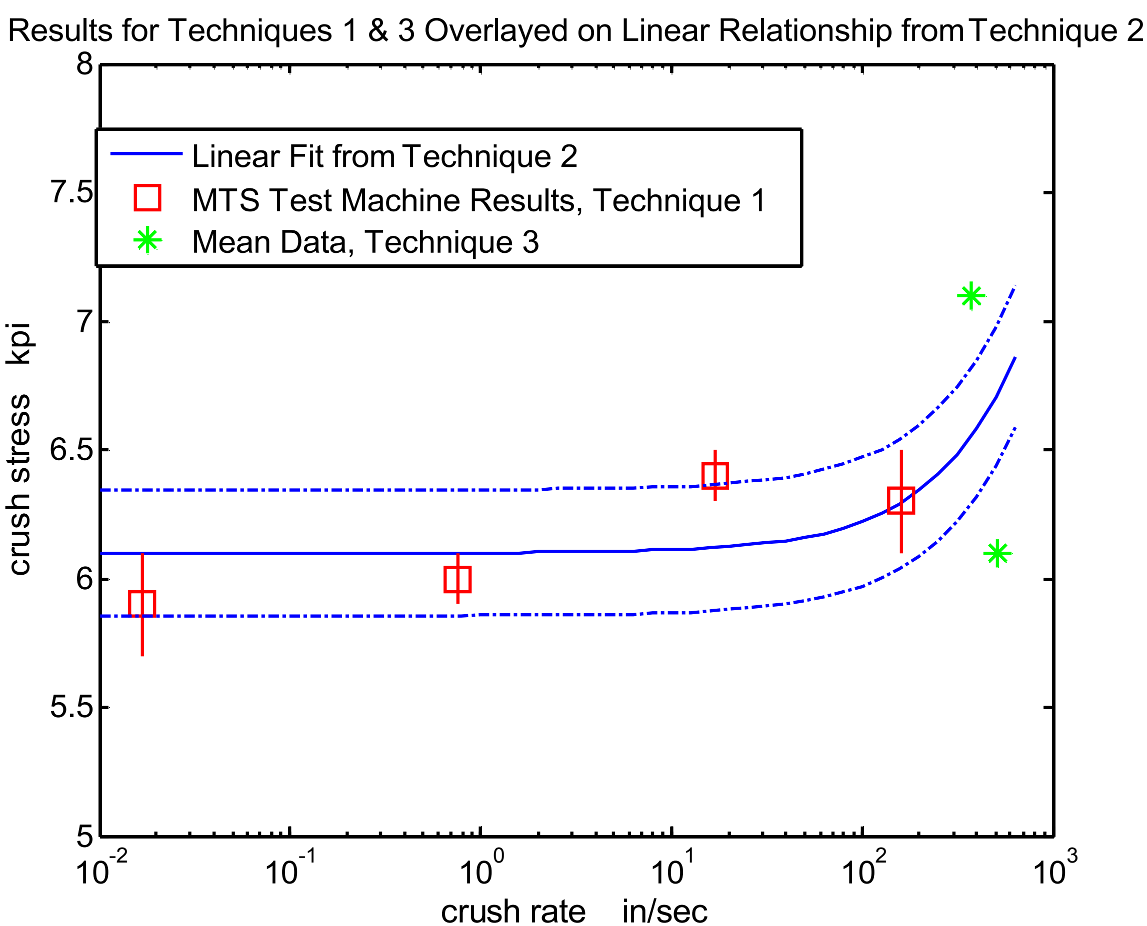
Generate distribution of model predictions based on random model parameter distributions of TS, LS, and WS crush strengths

Hypothesis: model is valid if Test data has sufficient overlap With model predictions

Statistical tests of hypothesis

There may be insufficient Evidence to reject the model for Cases A and B but sufficient Evidence to say it is invalid for Case C

Crush Stress vs. Velocity Test Data



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