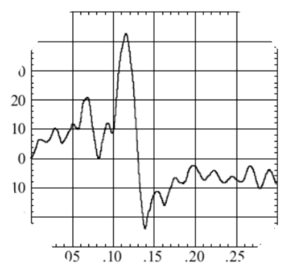
Standardization of Analytical and Experimental Methods for Crashworthiness Energy Absorption of Composite Materials (End of Year II)

Presented at the Fall AMTAS Meeting
Seattle, WA - Nov. 5th, 2009



Prof. Paolo Feraboli
University of Washington

Dr. Mostafa Rassaian
Boeing Research & Technology

New Laboratory

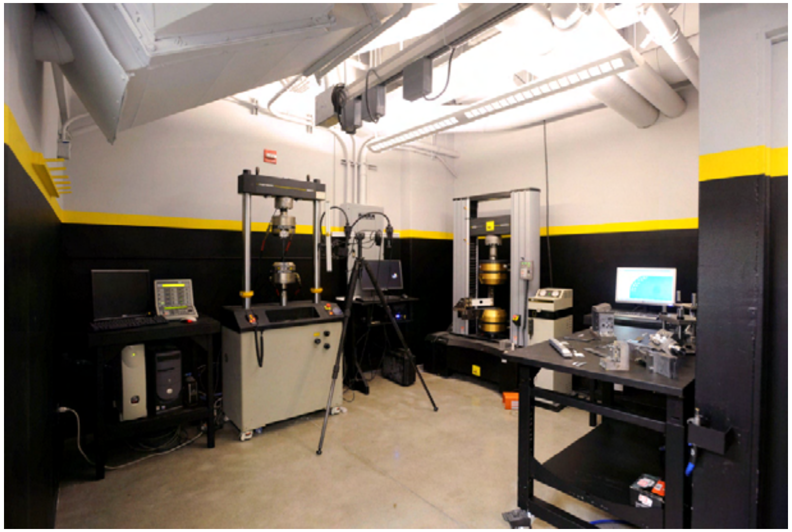
Automobili Lamborghini Advanced Composite Structures Laboratory (ACSL)

- Inaugurated Oct. 6th, 2009
- Collaborative R&D effort with The Boeing Co.
- Funding established Oct. 2007
- 5 full-time researchers
- 5-10 part-time research assistants

New Laboratory

Manufacturing and Characterization Facility

- Hot press
- VaRTM station
- Autoclave
- Fatigue and static test frames
- 3D Digital Image Correlation
- Ultrasonic C-scan immersion tank
- Mounting, polishing, microscopy
- Machining, bonding, repairs stations



Impact Dynamics Research Facility

- Full scale crash sled
- Gas guns for hail strike and bird strike
- Drop tower for low velocity impact
- Lightning strike generator
- Ultra-high speed camera

Computational Center

- Multiprocessor cluster for LS-DYNA

Outline

Motivation

- *Complete lack of standards and accepted practices in testing and analysis of composites under crash conditions*

Benefits to Aviation

- *Streamline certification process*
- *Increase confidence in analysis methods and therefore level of safety*

Objective

- *Develop experimental practices and analytical guidelines*

Outline

Principal Investigator

- *Dr. Paolo Feraboli*

Boeing Co-PI

- *Dr. Mostafa Rassaian*

FAA Technical Monitor

- *Allan Abramowitz*
- *Curt Davies and Dr. Larry Ilcewicz*

Industry Participation

- *Automobili Lamborghini S.p.A.*

Previous results

Crashworthiness

- *Current FE modeling strategies <u>are not predictive</u>*
- *Modeling strategies require the use of tweaking parameters that cannot be measured experimentally, need to be calibrated by trial and error, and may have no physical significance*
- *The need to produce numerical guidelines is very important to prevent users from running in gross mistakes associated with the selection of these parameters.*

- ***SOFT Parameter***
- ***Force-penetration curve***
- ***Contact formulation***
- *These parameters need to be calibrated using trial-and-error.*

Crushing of square tube

- *Trial and error procedure to find the “right” SOFT parameter that matches the experiment*
- *Vary only SOFT parameter*

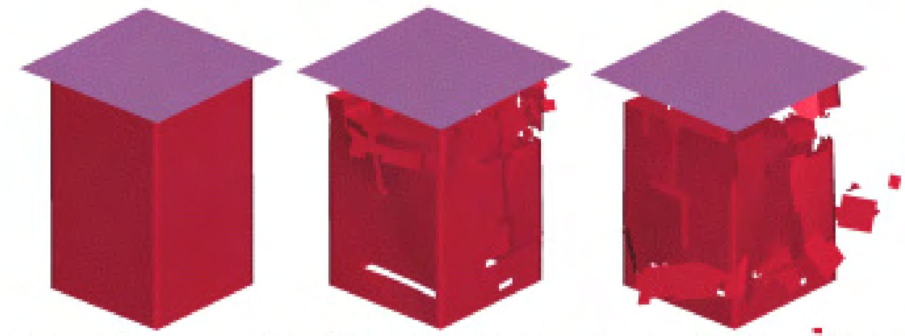


Figure 12. Example of an unstable crushing of the tubular shape with SOFT=0.64 Buckling starts after 2.446millsec at a displacement of 0.3669 inches.

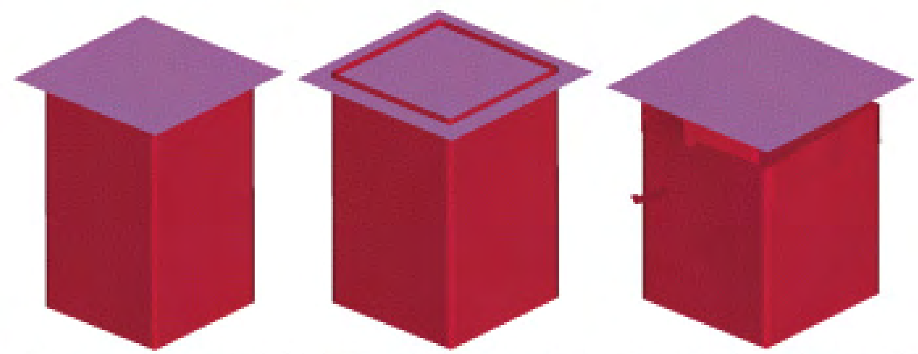


Figure 13. Example of an unstable crushing of the tubular shape with SOFT=0.3. Buckling starts after 3.728millsec at a displacement of 0.5592 inches.

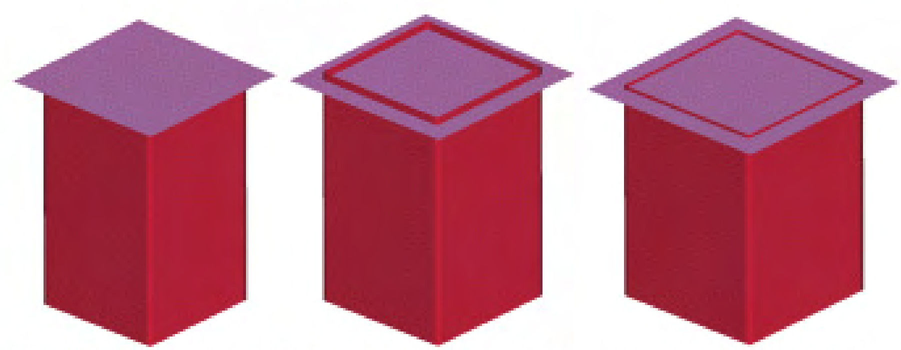


Figure 14. Example of a stable crushing of the tubular shape with SOFT=0.08. No buckling.

Crushing of other geometries

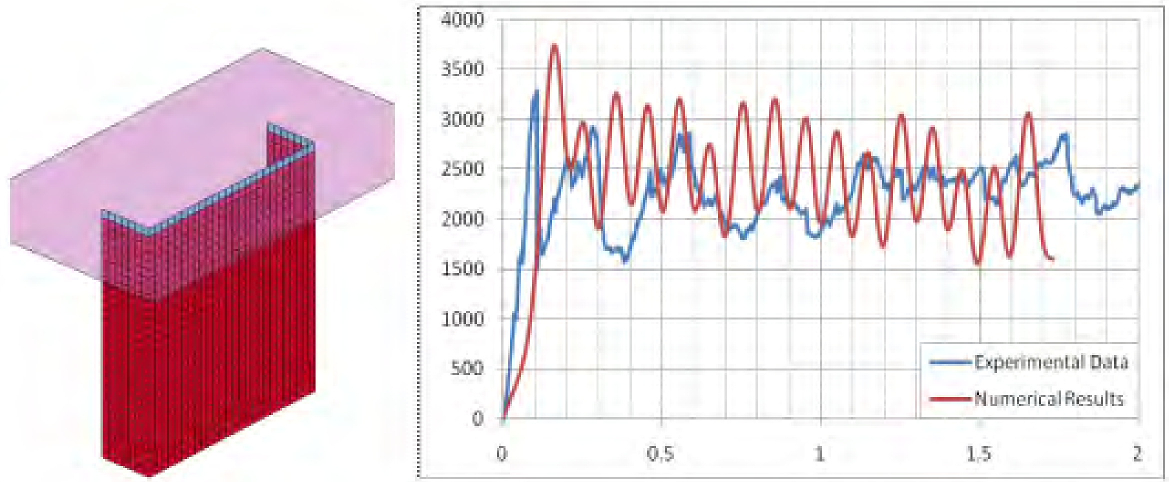


Figure 18. Model geometry and optimal Load-Displacement curve for the small C-Channel specimen.

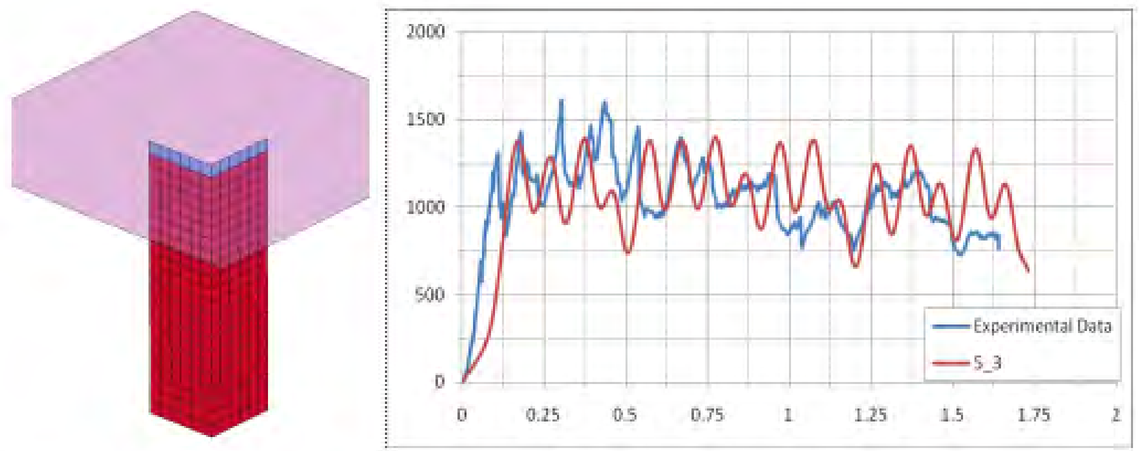


Figure 19. Model geometry and optimal Load-Displacement curve for the small corner specimen

Observations

- *For all geometries it is possible to find a suitable value of the SOFT parameter by trial and error*
- *Each geometry is characterized by a specific value of SOFT that matches the experimental data, while keeping all other parameters unchanged*
- *The same input deck cannot be used to predict all geometries “as-is”*
- *Thus the building block approach cannot be used “as-is” to scale from a coupon test to any other geometry*
- *SOFT parameter is a tweaking parameter….*

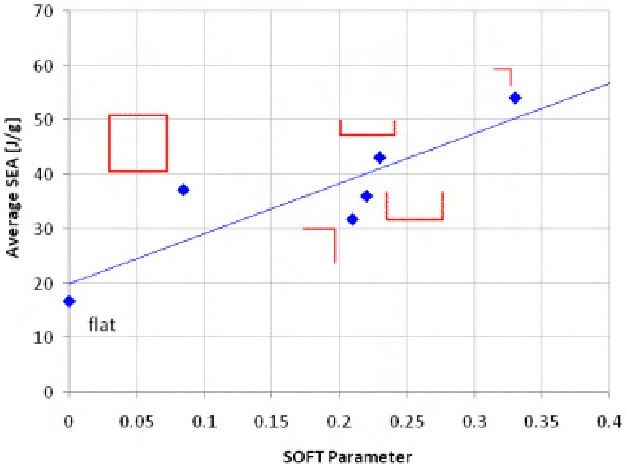


Figure 21. Linear relation between the SEA and the SOFT parameter

Case Study

PROGRESSIVE CRUSHING AND PENETRATION OF A DEEP SANDWICH COMPOSITE STRUCTURE: EXPERIMENT AND SIMULATION

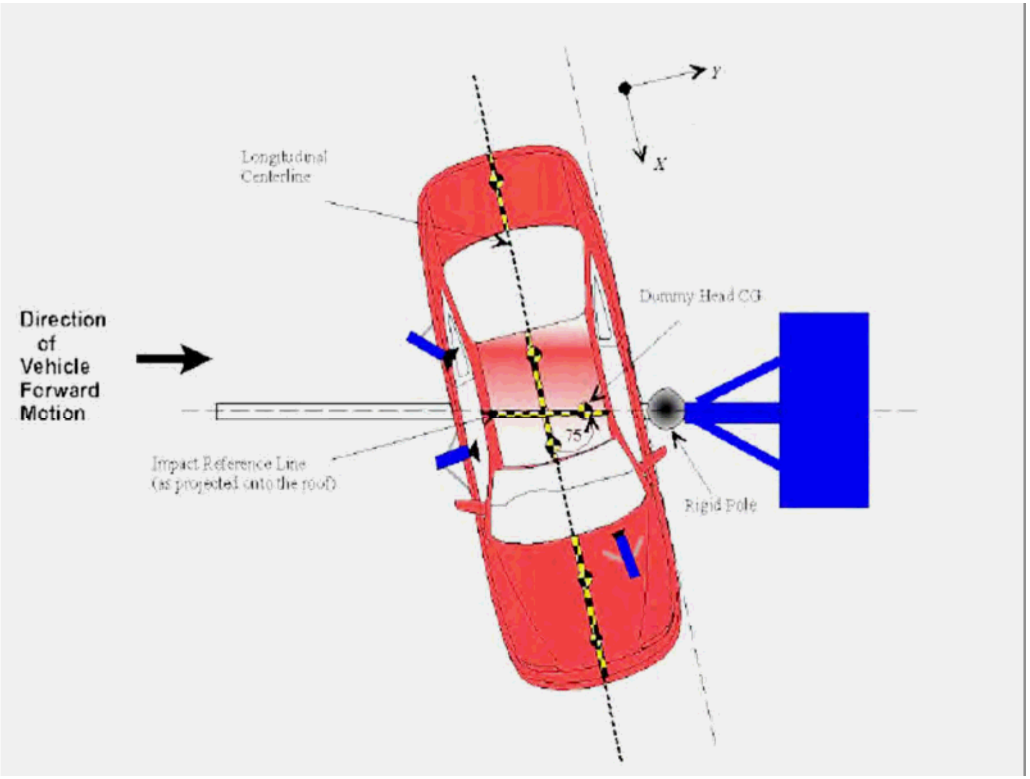
Paolo Feraboli*, Francesco Deleo, Bonnie Wade
Aeronautics & Astronautics, University of Washington, Seattle, WA

Mostafa Rassaian, Mark Higgins, Alan Byar
Research & Technology, The Boeing Co., Seattle, WA

Luciano DeOto, Attilio Masini, Giulia Fabbri
Research & Development, Automobili Lamborghini S.p.A., Sant'Agata Bolognese, Italy

Certification requirement

- FMVSS 214 Side Impact Protection
- Third part: Oblique Side Pole Impact Test
- 20 mph (32.2 km/h)
- Fixed steel pole 10 in. (254 mm) diameter.
- 75 degrees from the axis of the vehicle



Certification by analysis vs. testing

- In the automotive world a vehicle is certified (homologated) for crashworthiness by testing alone
  - Costly, time-consuming, requires long lead-times for re-development
  - Analysis is used in the design/ sizing stage

- Analysis methods for composites are not sufficiently predictive for the post-failure behavior

- Certification by analysis supported by test evidence
  - Derived from commercial aircraft industry
  - Adapted to automotive needs by Lamborghini
  - Reduces amount of large scale testing by using a mix of testing and analysis

Door sill technology demonstrator

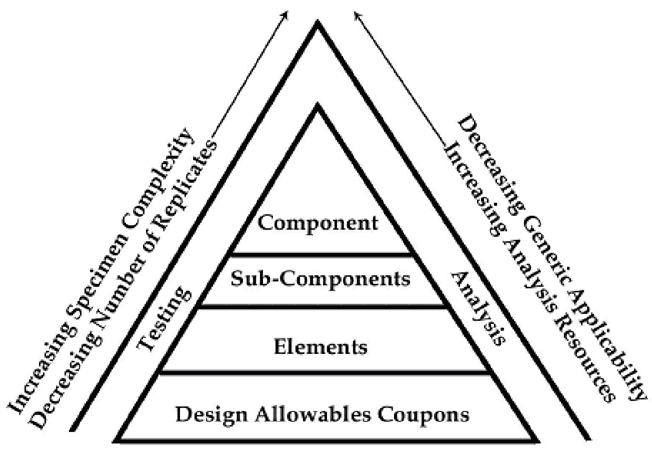
Partnership with Boeing

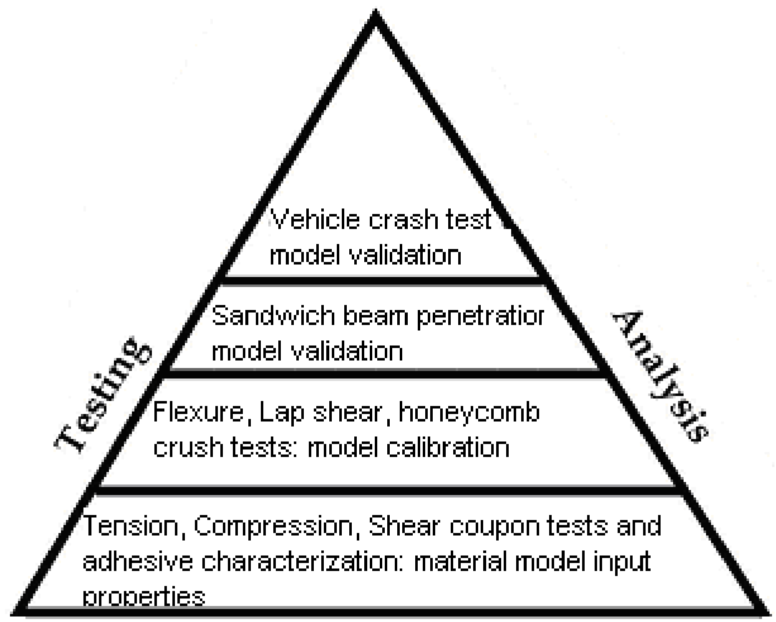
- Boeing Research & Technology (former Phantom Works)
- Structures Technology Group
- Advanced Analysis Team led by Mostafa Rassaian, Ph.D.
- Responsible for Boeing 787 Crashworthiness Analysis in support of certification
- First time CFRP fuselage was crash-tested and certified
- Utilized Building Block Approach

Door sill technology demonstrator

Application of the Building Block Approach

- Door sill FEA model can be isolated in key material models
  - MAT54 for facesheets
  - MAT126 for honeycomb core
  - Tie-break contact for adhesive joint
- Need to perform specific tests for each MAT model

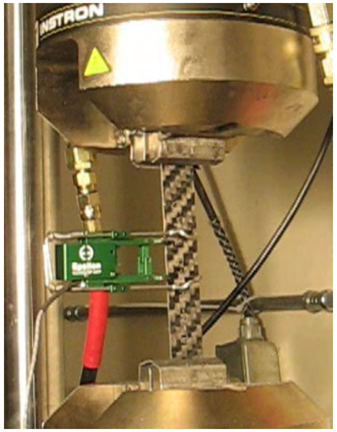


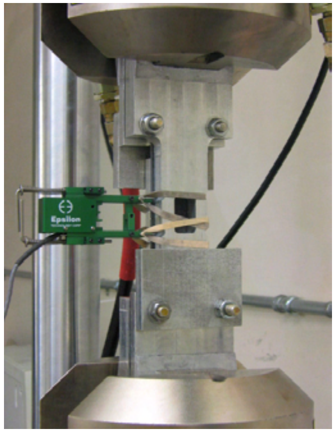
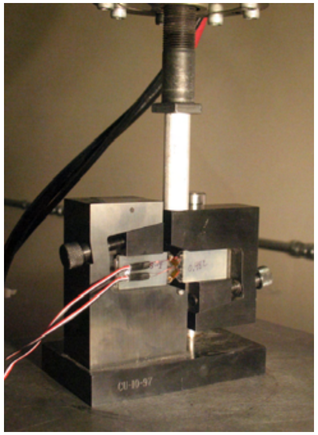


Door sill technology demonstrator

Coupon level testing

- PURPOSE: Generation of material model (material card in LS-DYNA)
- Generate allowables for tension, compression and shear (strength, strain and modulus)
- Represents real (not nominal) production process and includes effects of damage



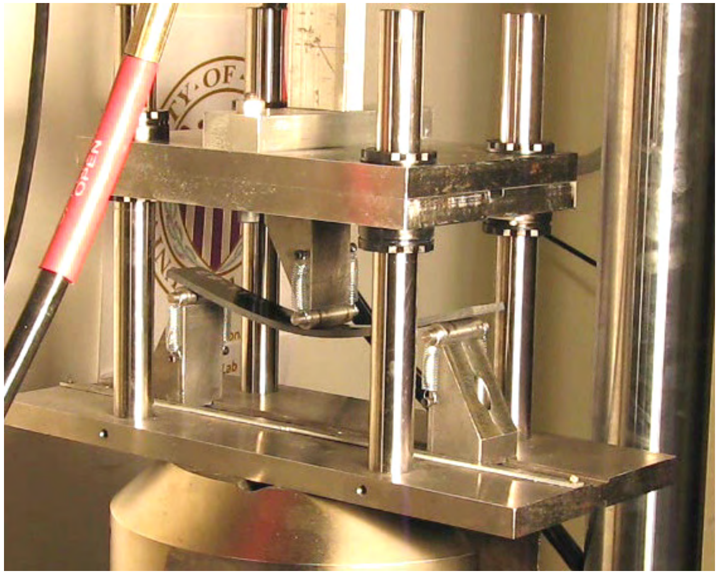
```
*MAT_LAMINATED_COMPOSITE_FABRIC_TITLE
MAT-58, Byar 081002
$ MATERIAL TYPE 58
$       MID        RO        EA        EB        EC      PRBA      TAU1    GAMMA1
         10 8.7500E-4 8.1000E+6 8.1000E+6 8.1000E+6  0.193000 13050.000  0.070000
$#      gab       gbc       gca    slimt1    slimc1    slimt2    slimc2     slims
 6.3800E+5 6.3800E+5 6.3800E+5  0.030000  0.060000  0.060000  0.010000  0.050000
$#     aopt     tsize     erods      soft        fs
     0.000 1.0000E-9  0.200000  0.600000 -1.000000
$#       xp        yp        zp        a1        a2        a3
     0.000     0.000     0.000     0.000     0.000     0.000
$#       v1        v2        v3        d1        d2        d3      beta
     0.000     0.000     0.000     0.000     0.000     0.000     0.000
$#     e11c      e11t      e22c      e22t       gms
  0.013000  0.015000  0.013000  0.015000  0.050000
$#       xc        xt        yc        yt        sc
 82500.000 1.1900E+5 82500.000 1.1900E+5 15950.000
```

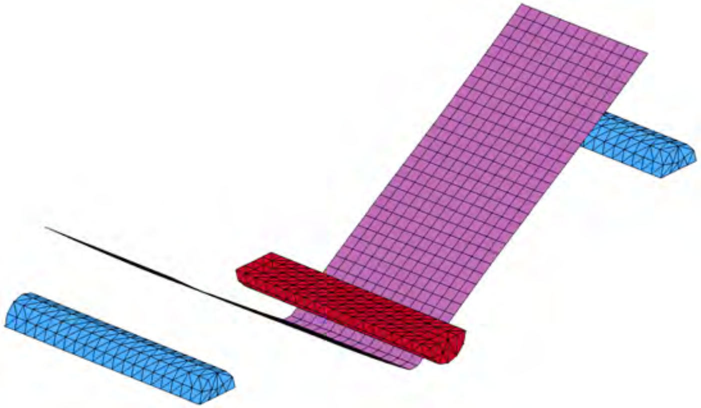
Door sill technology demonstrator

Element level testing

- PURPOSE: Calibration of material model
- MAT model Parameters are tuned to match experiment
- Three-point bend flexure test for carbon facesheet
- MAT 54 Enhanced composite material for facesheets

- 23 mins on 8-processor PC
- 3.2 GHz, 16 GB RAM

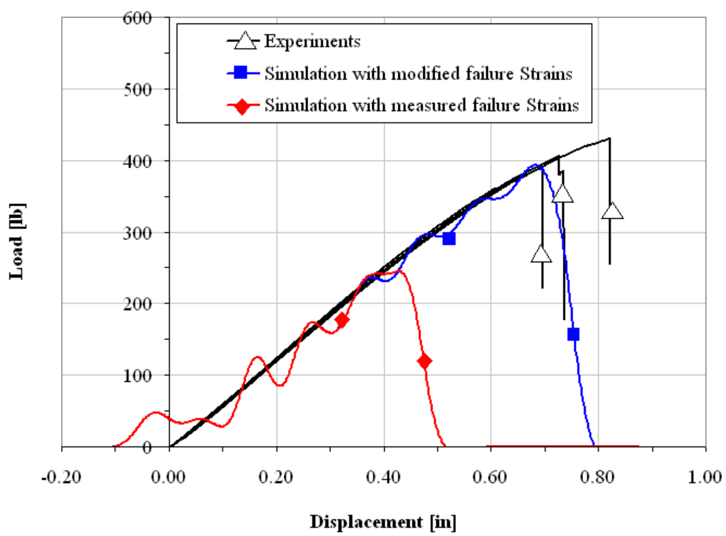


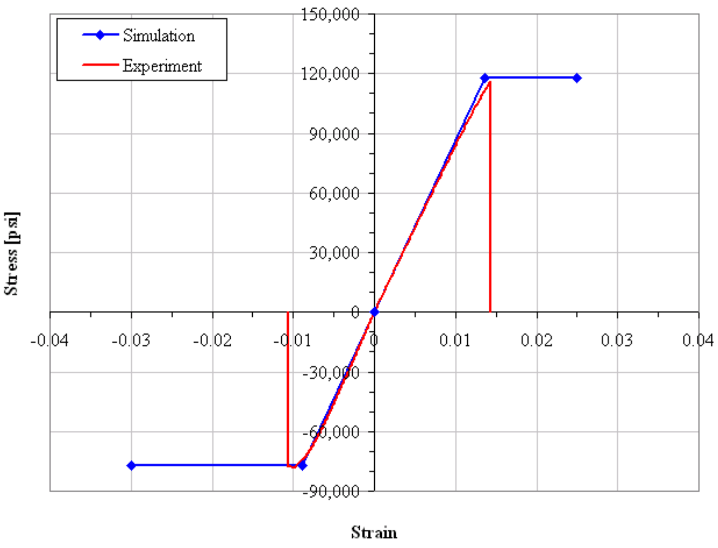


Door sill technology demonstrator

Example of calibration

- Experimental stress-strain curves in tension and compression (RED) lead to low failure load and displacement for flexure test simulation
- Need to virtually increase the strain-to-failure in order to match experimental data (BLUE)



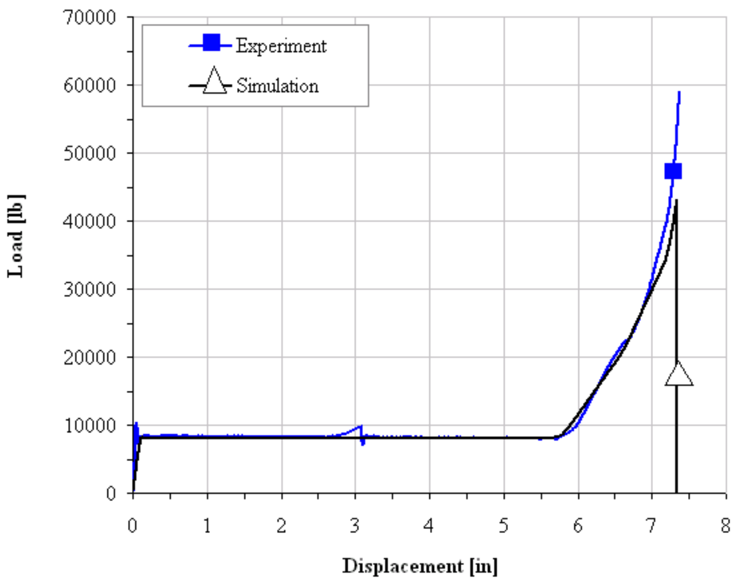


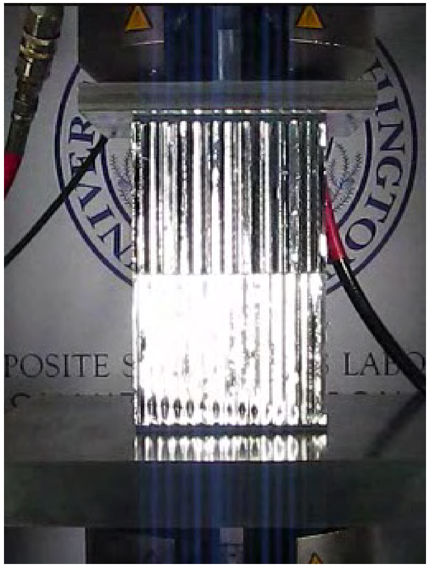
Door sill technology demonstrator

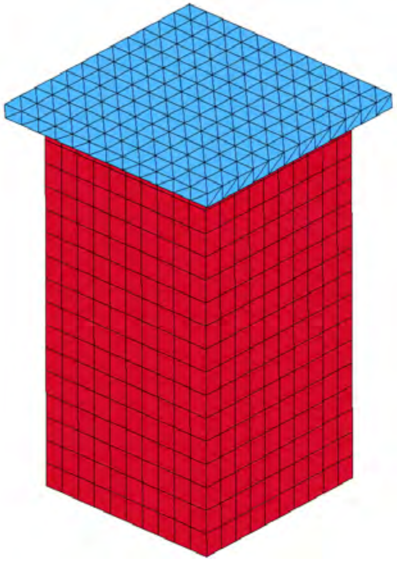
Element level testing

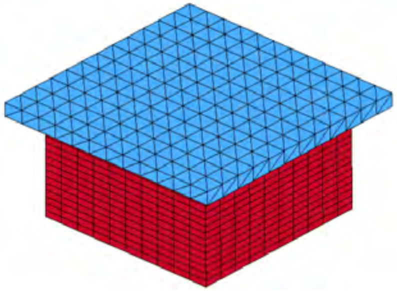
- PURPOSE: Calibration of material model
- Parameters are tuned to match experiment
- Stabilized honeycomb axial crushing
- MAT 126 metallic honeycomb
- L-D curve is fed into model itself (not predictive)

- 59 mins on 8-processor PC
- 2.8 GHz, 16 GB RAM





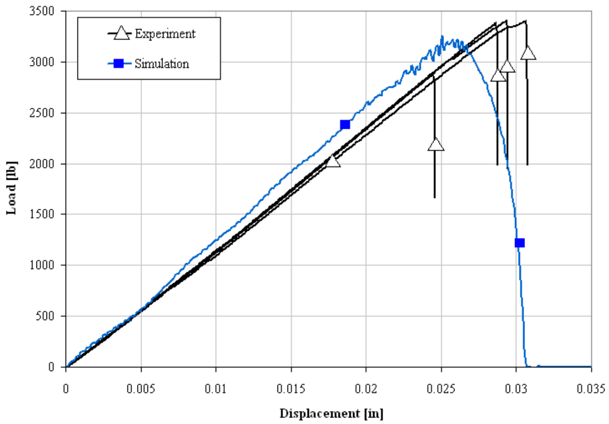




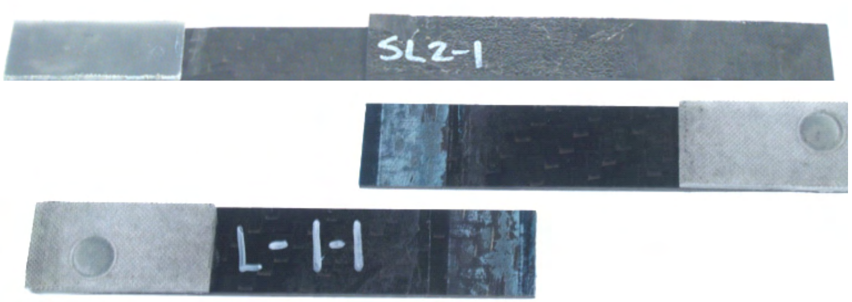
Door sill technology demonstrator

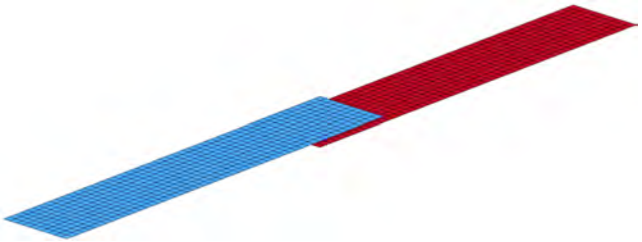
Element level testing

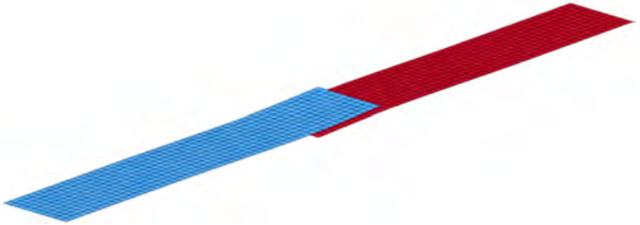
- PURPOSE: Calibration of contact/ joint
- Parameters are tuned to match experiment
- Single lap shear strength
- Tie-break contact definition for bonded joint



- 16 secs on 8-processor PC
- 3.2 GHz, 4 GB RAM





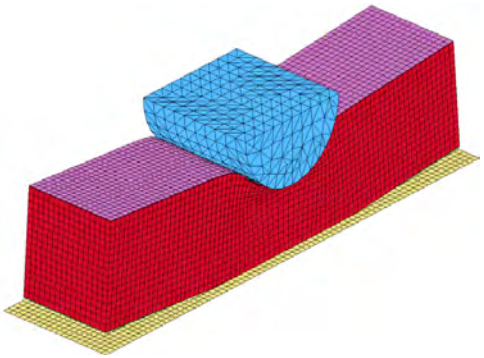


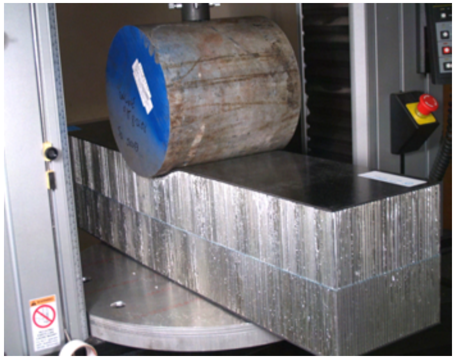
Door sill technology demonstrator

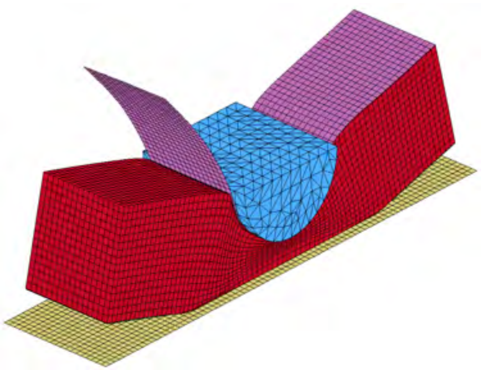
Sub-component level testing

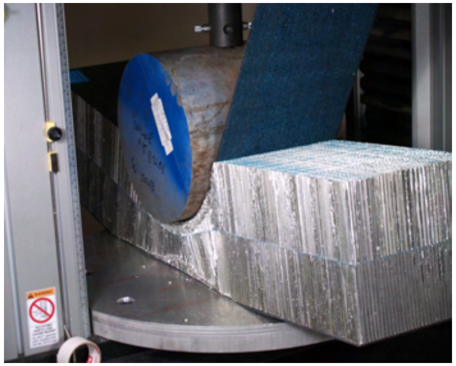
- PURPOSE: Validation of material model
- Full-scale model is assembled
- <u>Parameters CANNOT be changed to match experiment</u>
- Pole crushing of deep large beam
  - Materials and processing are consistent
  - FMVSS pole
  - Test rate is quasi-static
  - Simplified geometry
  - Boundary conditions representative

- 140 mins on 8-processor PC
- 3.2 GHz, 4 GB RAM





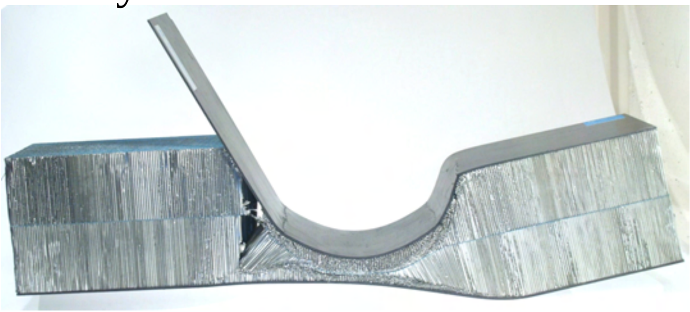


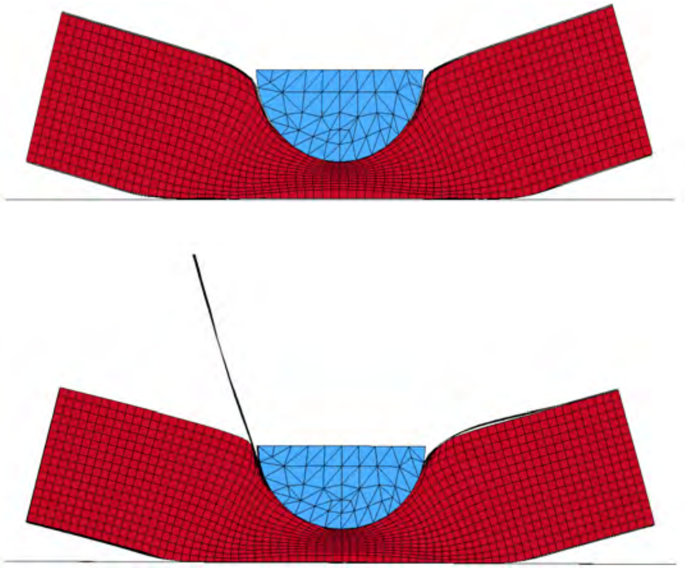


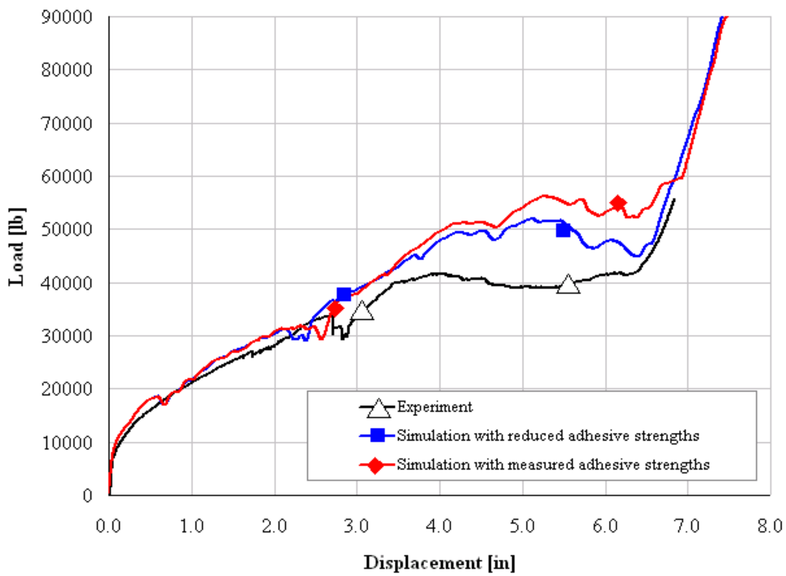
Door sill technology demonstrator

Sub-component level testing

- Simulation <u>needs to be predictive</u> at this level on the pyramid
- Changing the adhesive strength improves
  failure morphology but does not affect results significantly
- Adhesive area needs to be adjusted because of honeycomb cell surface area







Conclusions

- *The study has enabled the understanding of how MAT54 behaves under flexural and transverse crushing conditions, different from the axial crushing previously studied under FAA funding*
- *MAT126 and tie-break contact definitions were studied for the first time to understand their behavior*
- *These findings, together with previous one reported at JAMS and AMTAS 2008, will be summarized in a document containing guidelines for using LSDYNA*

Future work

- *Transition this knowledge to the case of FOD/ impact damage testing of honeycomb structures under concentrated loading (NASA BWB study)*