Jet Propulsion Laboratory
California Institute of Technology

# Earth Entry Vehicle Landing Analyses and HEEET Material Modeling for Potential Mars Sample Return

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*The decision to implement Mars Sample Return will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.*

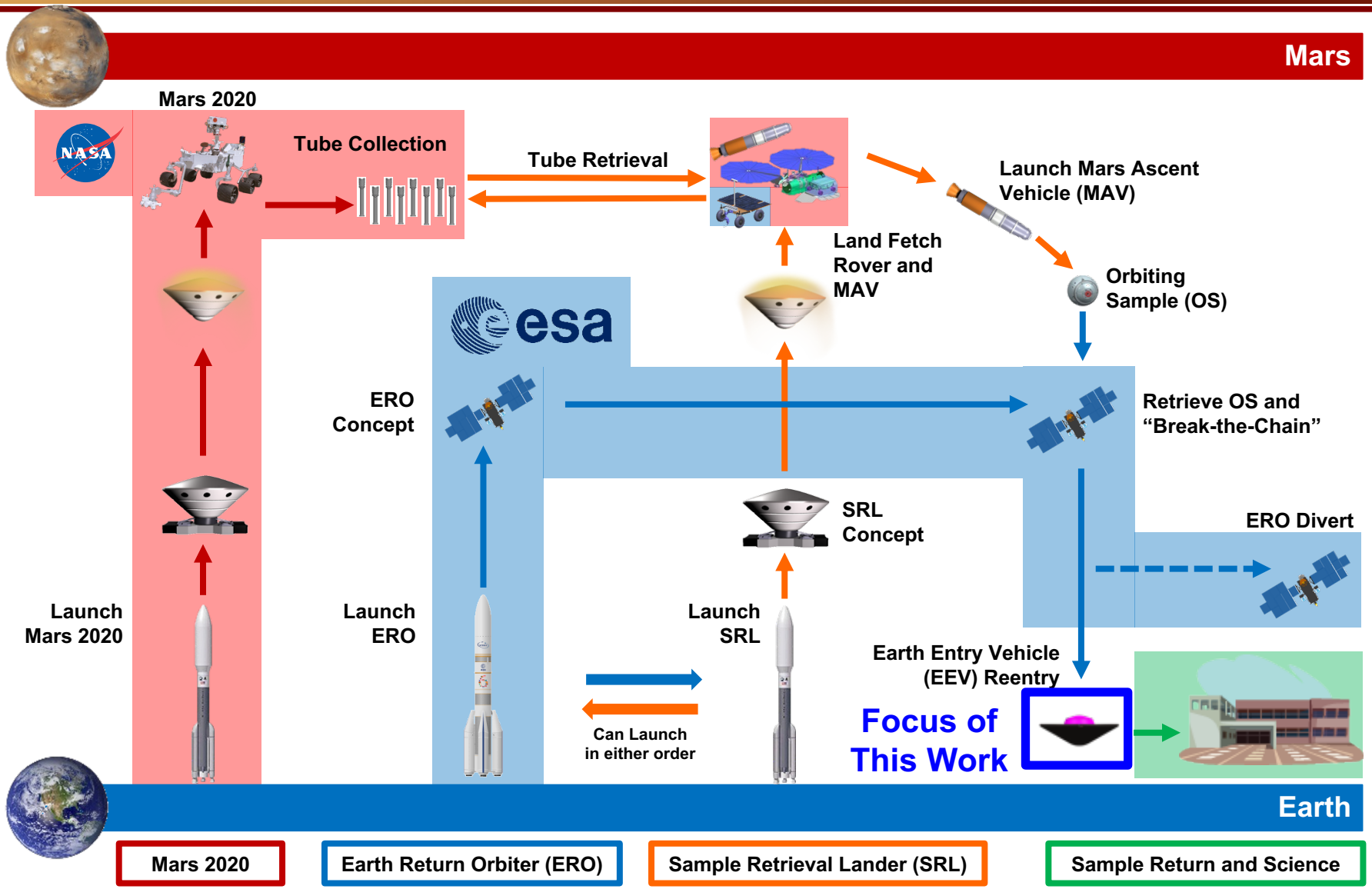
# Outline



- MSR Earth Entry Vehicle (EEV) Impact Landing Overview
- EEV Cellular Energy Absorber (CEA) Design
- Current EEV Designs
  - PICA TPS
  - HEEET S/IL & T/DL TPS
- EEV Off-Nominal Impact Analysis Using LS-DYNA
- CEA Coupon and Element Testing and Model Validations
- CEA Design iterations
- HEEET TPS and CEA Performance
- HEEET Testing and Model Development
- PICA vs. HEEET Hard Surface Impact
- Conclusions & Future Work

# MSR Concept Architecture*

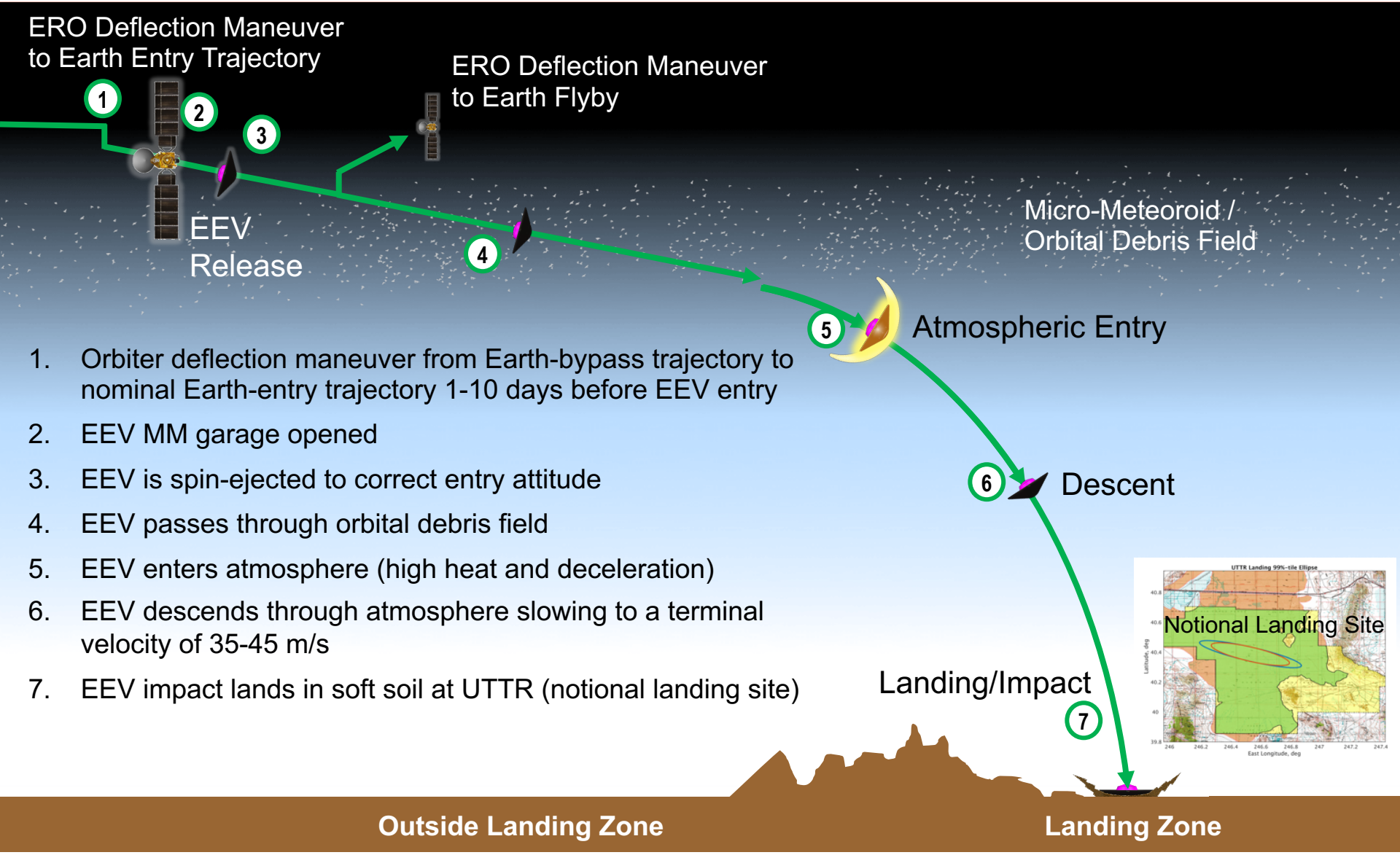





*Per NASA/ESA Joint Statement of Intent, 26 April 2018

# Notional Earth Return Profile



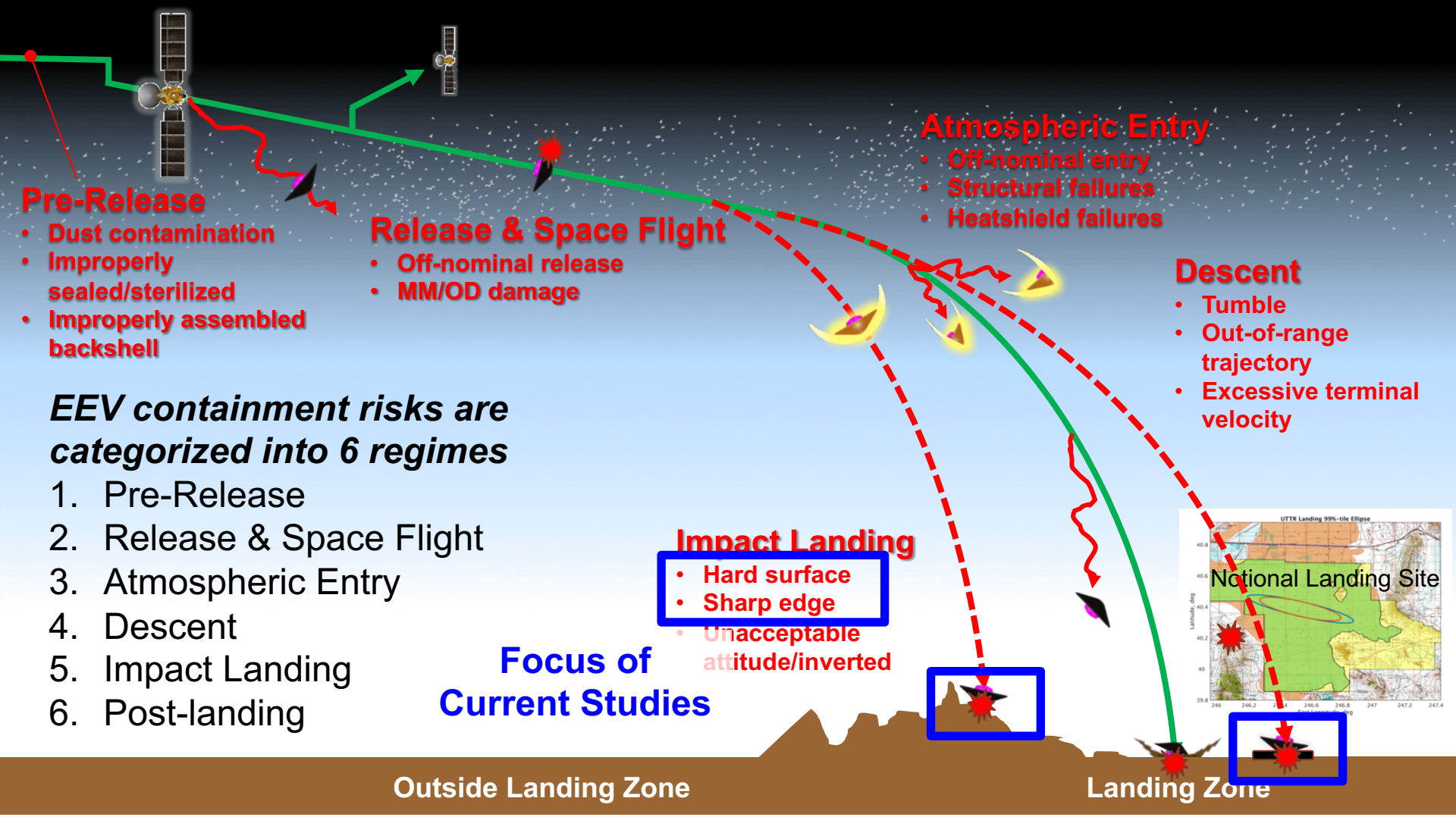



1. Orbiter deflection maneuver from Earth-bypass trajectory to nominal Earth-entry trajectory 1-10 days before EEV entry
2. EEV MM garage opened
3. EEV is spin-ejected to correct entry attitude
4. EEV passes through orbital debris field
5. EEV enters atmosphere (high heat and deceleration)
6. EEV descends through atmosphere slowing to a terminal velocity of 35-45 m/s
7. EEV impact lands in soft soil at UTTR (notional landing site)

# Notional Earth Return Profile – Risks



**** Examples of potential off-nominal situations shown in in red***




***EEV containment risks are categorized into 6 regimes***

1. Pre-Release
2. Release & Space Flight
3. Atmospheric Entry
4. Descent
5. Impact Landing
6. Post-landing

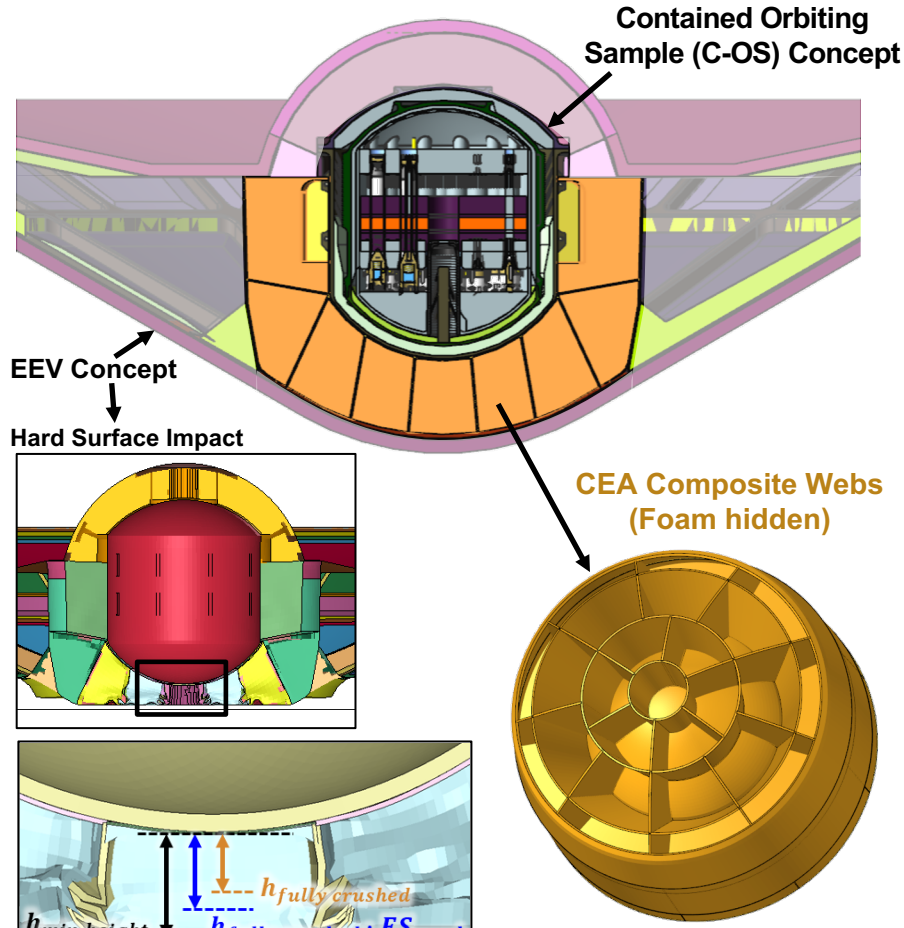
# EEV Design Considerations for Off-Nominal Landing



***Ability to survive an off-nominal impact and limit C-OS loads to manageable levels is critical to achieving a highly reliable, low-risk sample return system***

- **In off-nominal events, not required to maintain scientific integrity of returned samples**
  - Primary goal: Preserve containment
- **Estimate C-OS can be designed to withstand 3000 G**
  - Design, analysis, and testing is being conducted in FY19 to verify
- **Cellular energy absorber (CEA) mitigates C-OS loads during off-nominal impact**
  - Formed by wrapping carbon foam cells with composite, then assembling and co-curing
  - Estimate fully crushed height is 25% of initial; apply safety factor to avoid full crushing

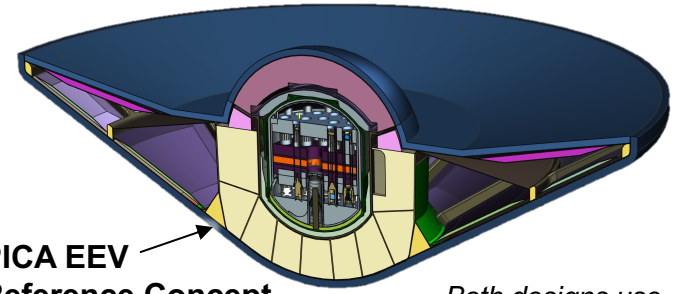
| Performance Metrics | Allowable | F.S. |
|---|---|---|
| 1. C-OS Loading | 3000 G | 1.0 |
| 2. CEA Crushed height | 25% | 1.3 |



# Current EEV Designs and Landing Characteristics

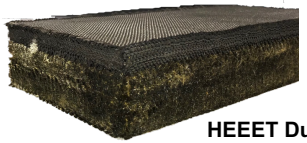


- **Two TPS materials under consideration**
  1. PICA (low density carbon phenolic)
     - Pressure-heating capability for EEV environment only sparsely demonstrated
     - For impact landing, PICA considered non-structural mass
  2. HEEET (3D woven carbon phenolic)
     - Higher MM/OD resistance than PICA
     - Demonstrated capability well within EEV pressure-heating environment
     - Heavier EEV with ~2x kinetic energy as PICA EEV at impact
     - Stiffer/more structural than PICA; may not be able to ignore during off-nominal impact

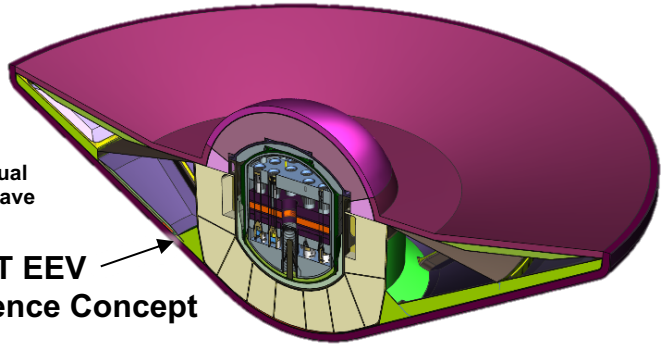


**PICA EEV Reference Concept**

*Both designs use PICA backshell TPS*



**HEEET Dual Layer Weave**



**HEEET EEV Reference Concept**

- **Both reference designs utilize the same cellular energy absorber concept**

- **Landing characteristics for each EEV concept based on ED&L analysis by NASA LaRC**

**PICA Concept Landing Characteristics**

| Parameter | Unit | 0.13% | Mean | 99.87% |
|---|---|---|---|---|
| Vertical Velocity | m/s | 32.4 | 34.8 | 37.5 |
| Impact Angle | deg | 0.5 | 7.1 | 15.7 |

**HEEET-DL Concept Landing Characteristics**

| Parameter | Unit | 0.13% | Mean | 99.87% |
|---|---|---|---|---|
| Vertical Velocity | m/s | 37.6 | 40.5 | 43.4 |
| Impact Angle | deg | 0.3 | 7.1 | 17.3 |

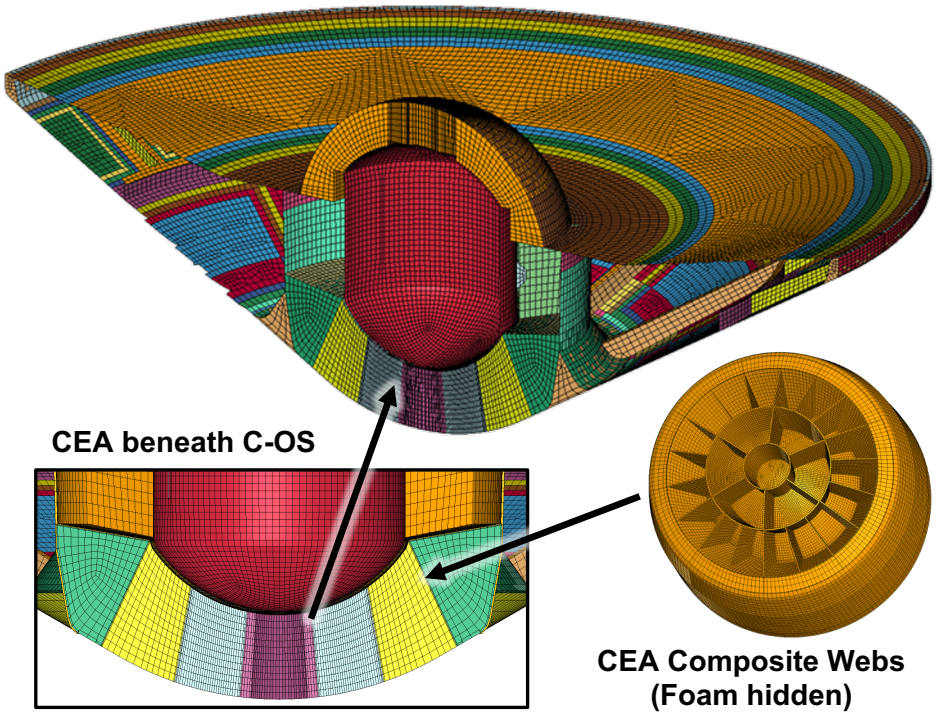
**Reference Masses and Energy at Impact (99.87% velocity)**

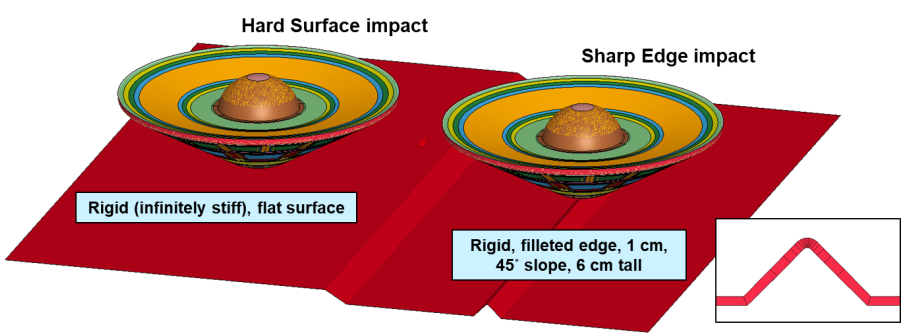
| Design | Mass (kg) | Energy (kJ) |
|---|---|---|
| PICA | 63.3 | 44.5 |
| HEEET-SL | 80.3 | 75.6 |
| HEEET-DL | 85.0 | 80.1 |

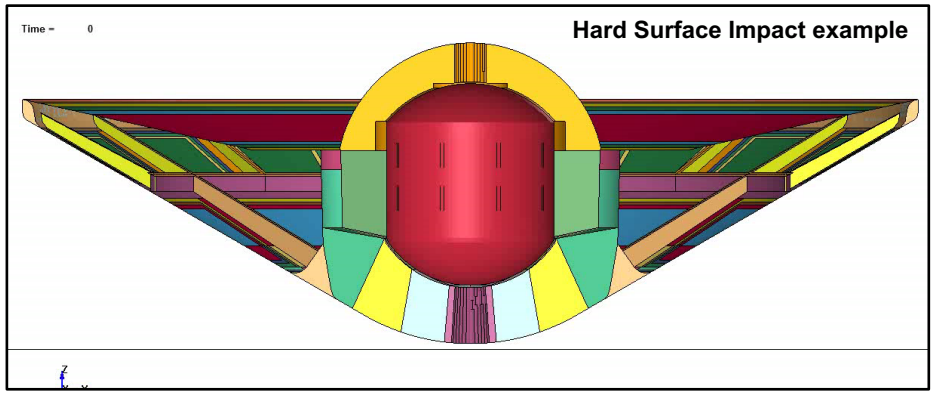
# Off-Nominal Impact Analysis Using LS-DYNA



- **All parts of the EEV are explicitly modeled**
  - Foams modeled with solid elements
  - Composite webs, forward body shell, and most other parts modeled with shells
  - C-OS is simplified to SCV shell with an assigned mass (currently 23 kg)
- **Highly non-linear analysis involving:**
  - Large deformation
  - Material nonlinearity & Composite failure
  - Complex contact
- **Must conduct early testing to validate models**
  - Early in design process, test coupons and representative elements of critical components
    - For off-nominal impact, the energy absorber is the most critical component
  - First steps of traditional "building block approach"
  - ***Once validated, models are a critical design tool***



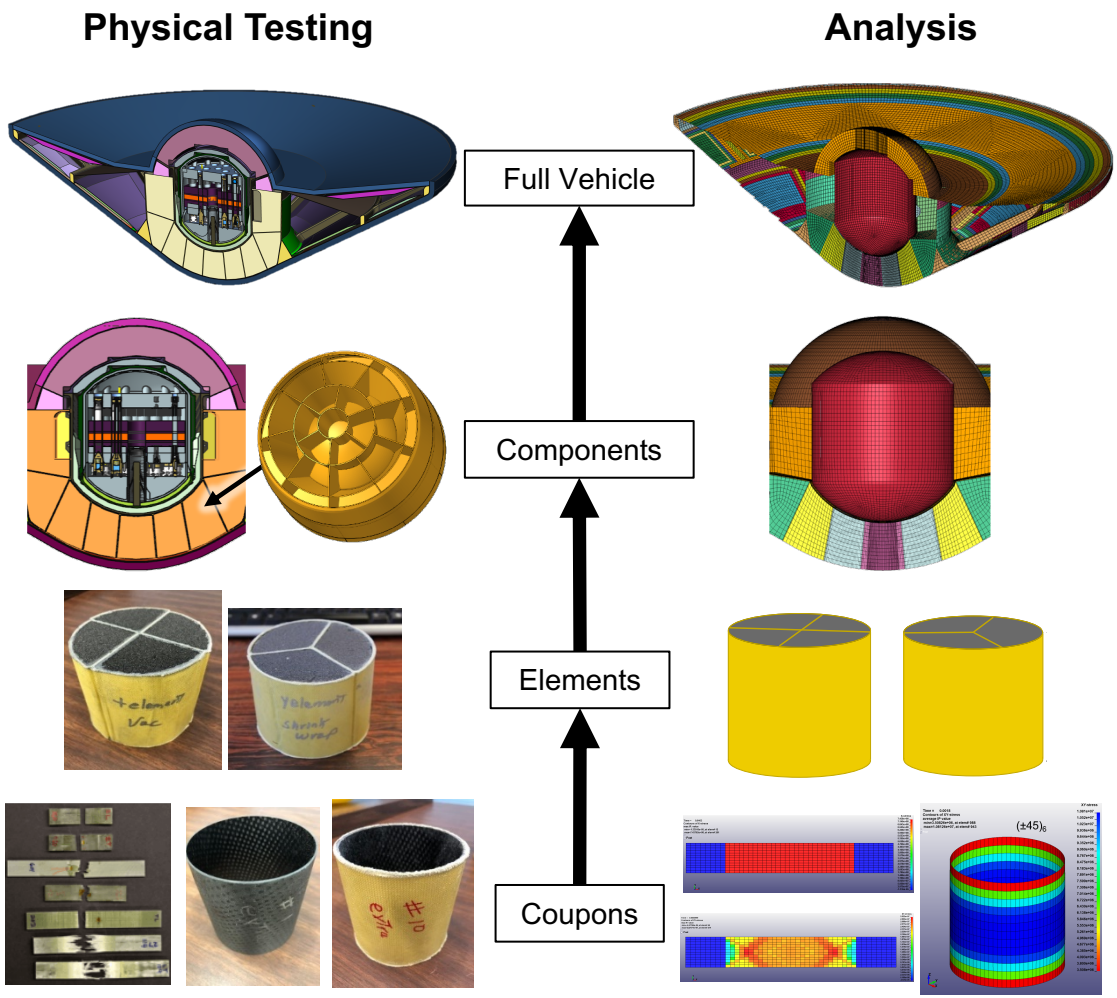



# CEA Modeling for Impact
## Building Block Approach



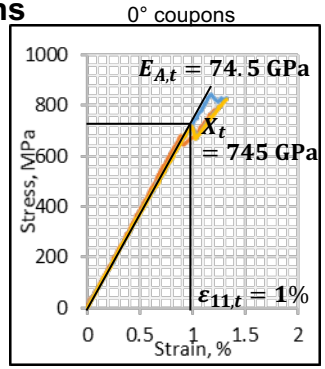
- **Traditional method of developing validated models of complex system and phenomena**
  - Concurrent physical testing and analysis
- **Starting point is coupon and representative elements**
- **Candidate CEA web materials:**
  - IM7 5HS fabric
  - Kevlar-129 plain fabric
  - TC420 cyanate ester resin matrix

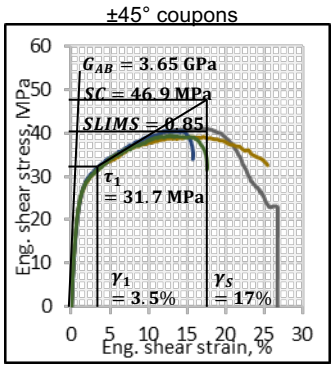


# IM7/RT-Epoxy
## Initial Model Inputs Derived from Test Data

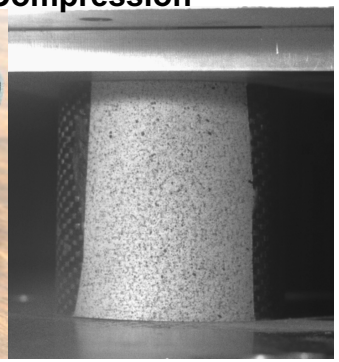


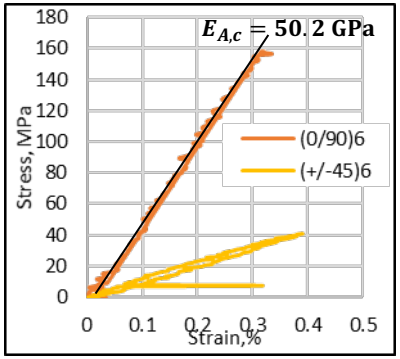
### Static Tensile Coupons



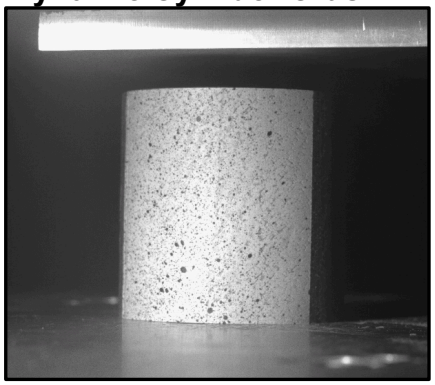



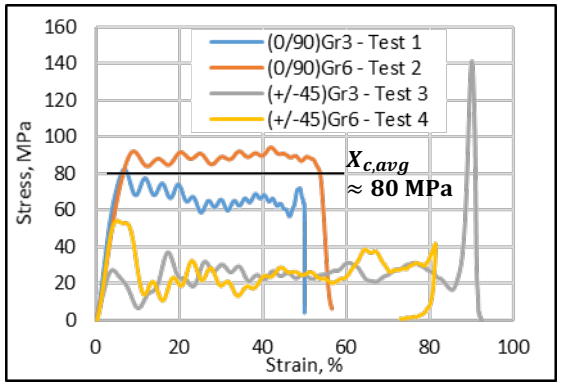

### Static Cylinder Compression






### Dynamic Cylinder Crush



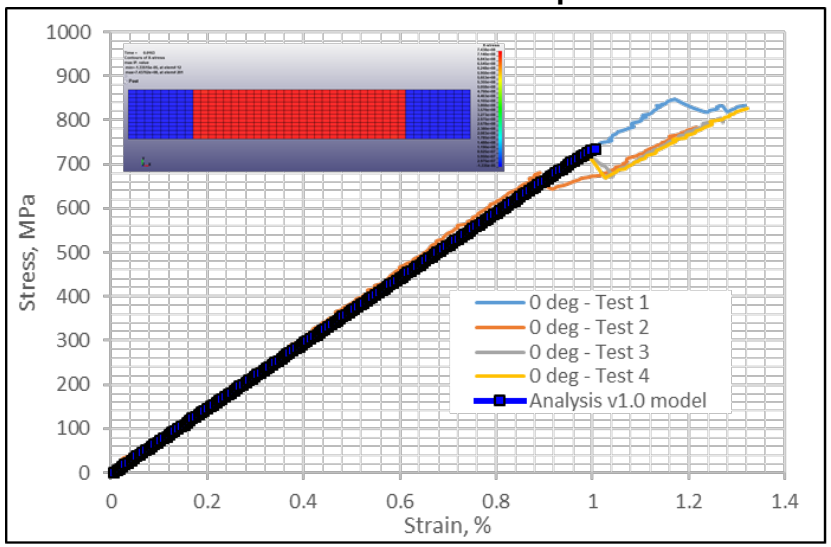


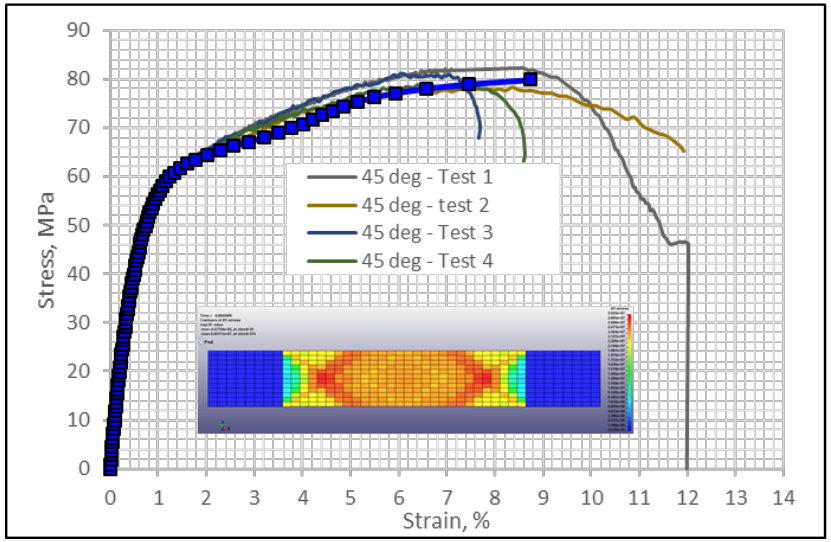

| | | IM7/RT-Epoxy 5HS 6k Fabric |
|---|---|---|
| **Physical Data or Model** | | **Model (v1.0)** |
| **Speed basis** | | Hybrid |
| **Temperature basis** | | RT |
| **Ply thickness** | mm | 0.33 |
| **Physical prop / *MAT_58 Param** | **Description** | |
| RHO | Density, kg/m³ | 1496 |
| EA/EB, tension | Young's modulus, GPa | 74.5 |
| EA/EB, compression | Young's modulus, GPa | 50.2 |
| EC[a] | Young's modulus, GPa | 50.2 |
| PRAB | Poisson's ratio | 0.05 |
| PRBC/PRAC | Poisson's ratio | 0.05 |
| GAB | Shear modulus, GPa | 3.65 |
| GBC/GAC | Shear modulus, GPa | 3.65 |
| SLIMT1/SLIMT2 (Mat_58) | Min. stress limit – tension | 0.1 |
| SLIMC1/SLIMC2 (Mat_58) | Min. stress limit – compression | 1.0 |
| SLIMS (Mat_58) | Min. stress limit – shear | 0.85 |
| ERODS (Mat_58) | Max. eff. strain for layer failure | - |
| E11C/E22C | Max. compressive strain | 0.00165 |
| E11T/E22T | Max. tensile strain | 0.01 |
| TAU1 | Shear stress at non-linear, MPa | 31.7 |
| GAMMA1 | Shear strain at non-linear | 0.035 |
| GMS | Max. shear strain | 0.17 |
| XC/YC | Max. compressive stress, MPa | 80.0 |
| XT/YT | Max. tensile stress, MPa | 744.6 |
| SC | Max. shear stress, MPa | 46.9 |
| SOFT | Softening reduction factor | - |
| FS | Failure surface | -1 (uncoupled) |

# IM7/RT-Epoxy
## Static Tests vs. Analyses

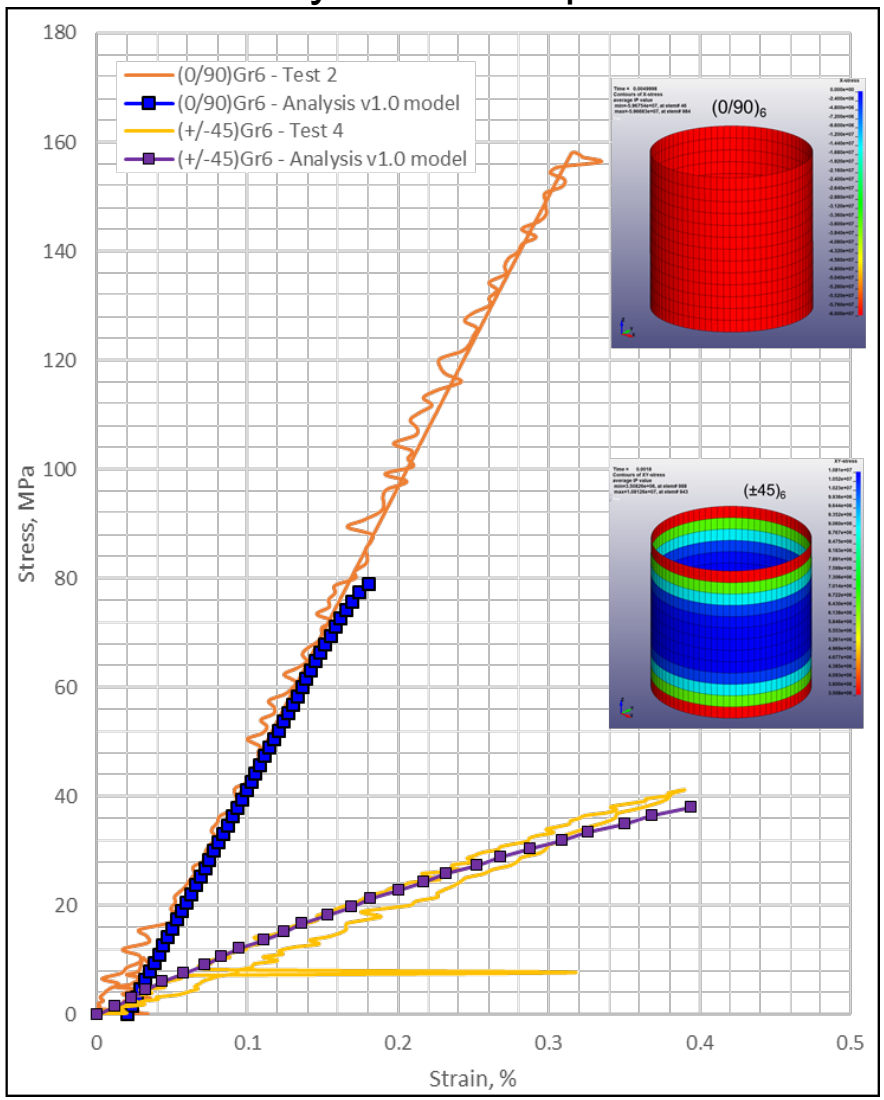


### Static Tensile Coupons



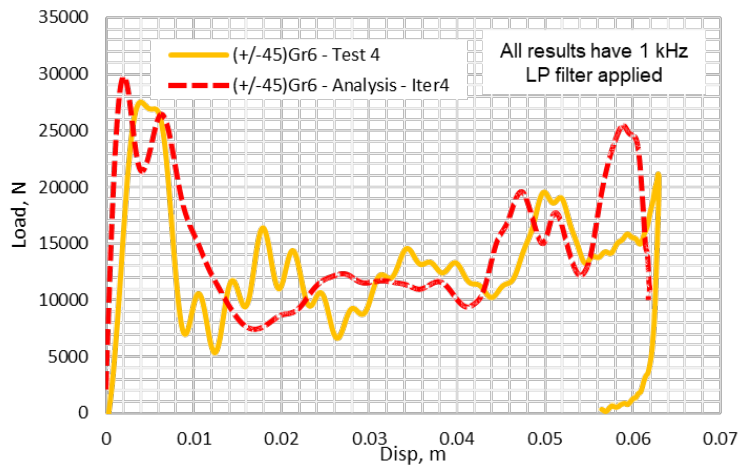

### Static Cylinder Compression

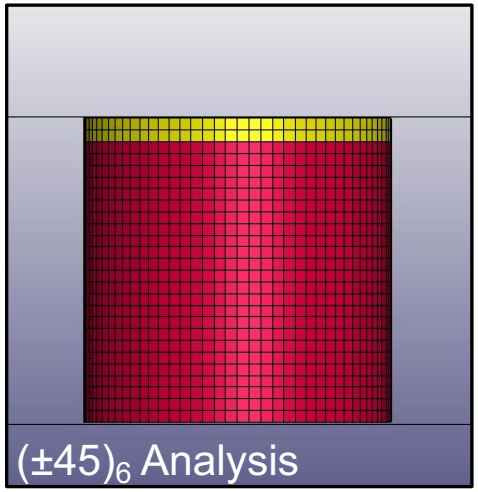


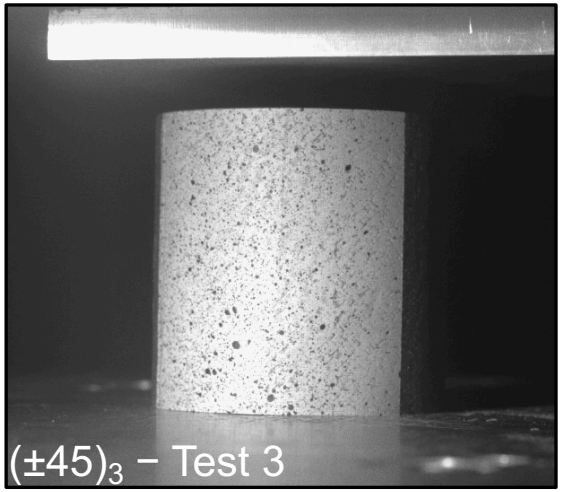
# IM7/RT-Epoxy
## Cylinder Crush Tests vs. Analyses

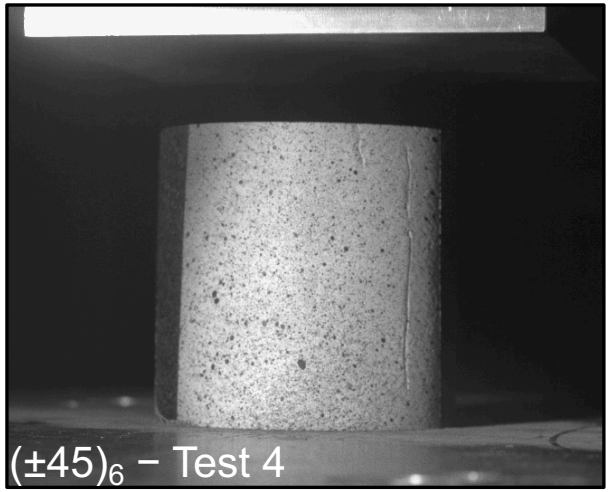


- **Goal: Match energy absorbed, load history, and deformed shape during crushing**
  - Load history and deformation behavior do not need to match exactly; general agreement is sufficient
- Example: $(\pm 45)_6$ analysis
  - Corresponds to Test 4
- Initial wrinkle in Test 4 may have altered folding behavior, so Test 3 video is also shown for comparison
  - Expect that without initial wrinkle, Test 3 and 4 folding would have been more similar
- **Result: Energy absorbed, loads, and deformation match well**
  - Very few mods needed; biggest change was trigger to encourage failure on same side at the test
  - Gives credence/validity to the material model used (LS-DYNA Mat58 w/ shells)



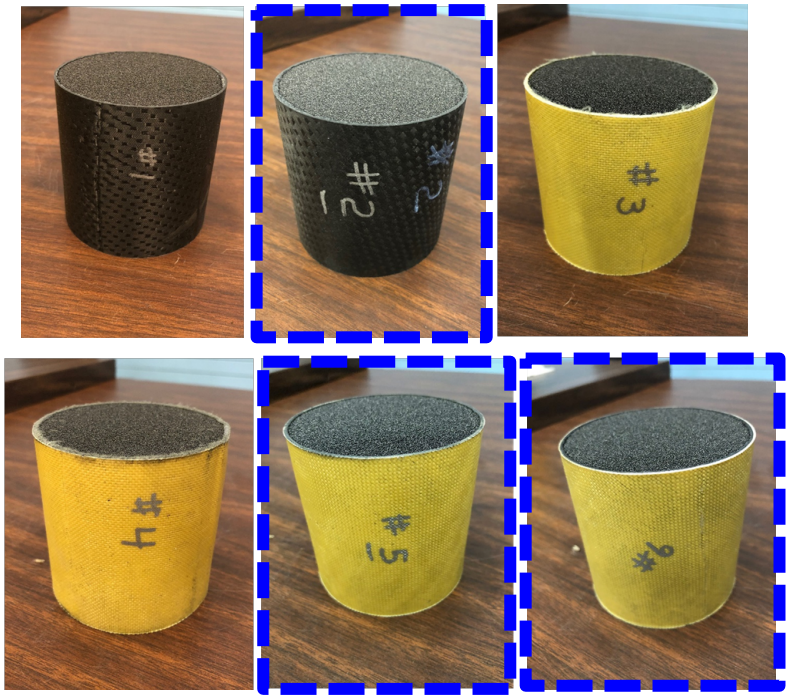




High speed videos

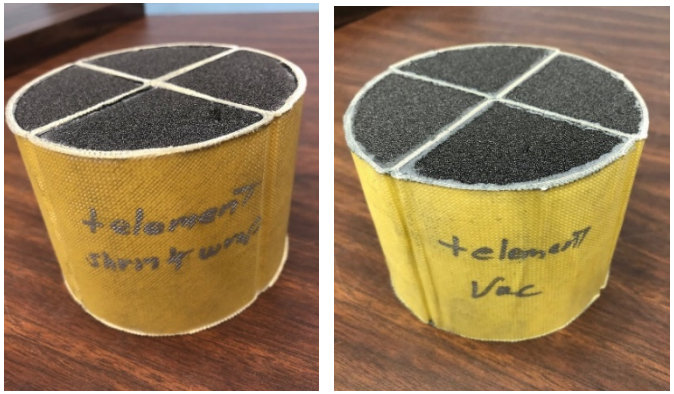
# Dynamic Crush Test Articles
# Foam-Filled Cylinders and Elements



***Crush tests are completed; Data post-processing and modeling underway***




| Specimen | Layup | Weight, g | Diameter, in | Height, in |
|---|---|---|---|---|
| Cylinder #1 | $(0/90)_3$ gr | 48 | 3.079 | 3.045 |
| Cylinder #2 | $(\pm45)_3$ gr | 50 | 3.069 | 3.094 |
| Cylinder #3 | $(0/90)_3$ k | 47 | 3.113 | 3.026 |
| Cylinder #4 | $(0/90)_6$ k | 67 | 3.153 | 3.129 |
| Cylinder #5 | $(\pm45)_3$ k | 44 | 3.066 | 2.968 |
| Cylinder #6 | $(0/90)_2$ gr / $(\pm45)_2$ k | 57 | 3.068 | 3.033 |



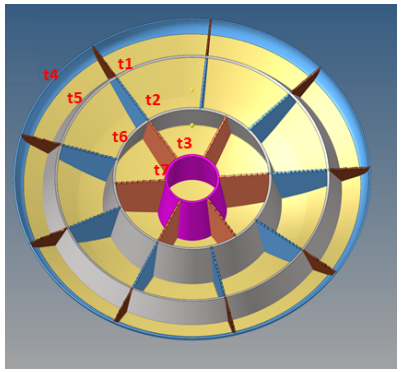

| Specimen | Weight, g | Diameter, in | Height, in |
|---|---|---|---|
| + Elements: Shrink Wrap | 138 | 4.090 | 2.954 |
| + Elements: Vacuum | 142 | 4.084 | 3.038 |

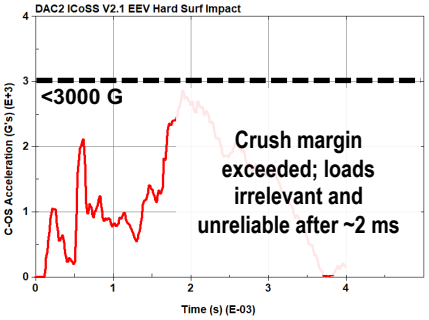
| Specimen | Weight, g | Diameter, in | Height, in |
|---|---|---|---|
| Y Elements: Shrink Wrap | 131.2 | 4.035 | 2.984 |
| Y Elements: Vacuum | 127.7 | 4.071 | 3.0175 |

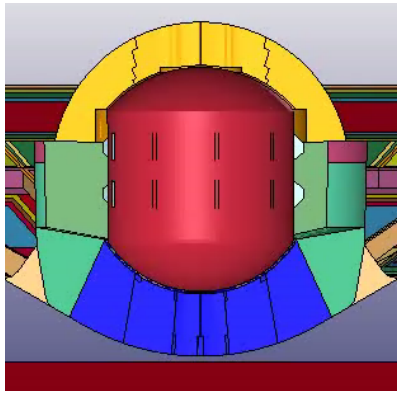
# CEA Web Pattern and Layup Iterations
## Hard Surface Impact



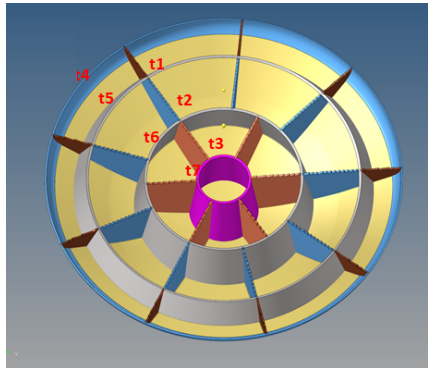
V2.1: DAC2 starting design

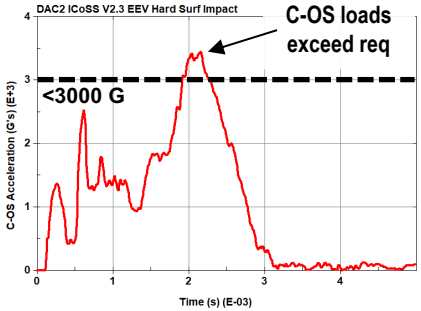


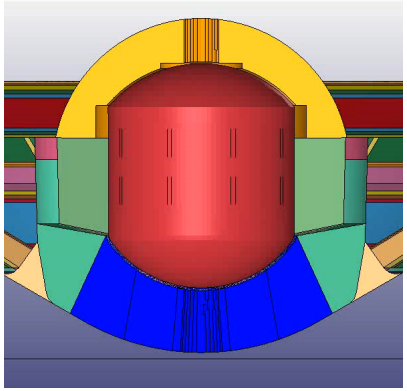



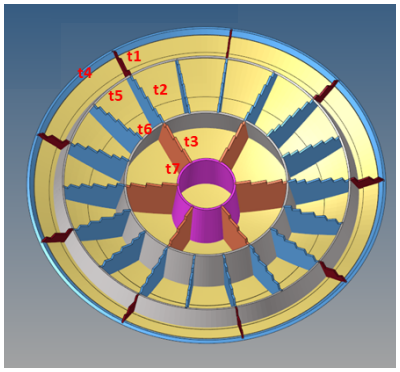
V2.3: Increased thickness of central webs ~66% (t3,t7,t6)

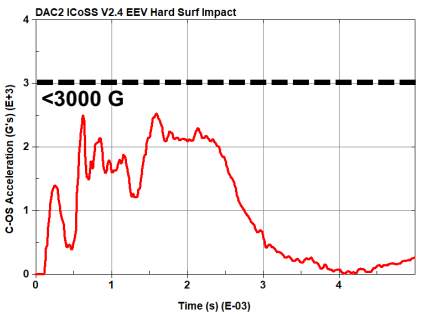


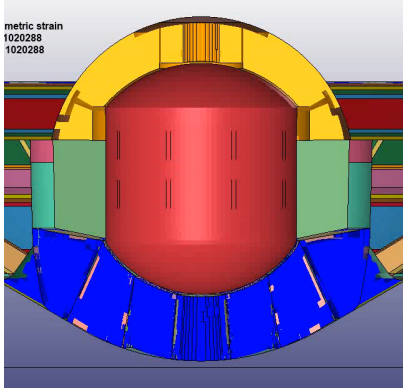



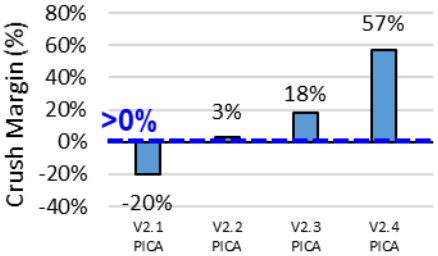



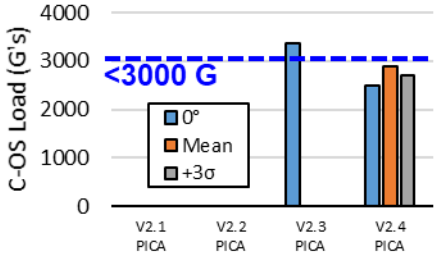
V2.4: Added more webs (t2) to outer hoop

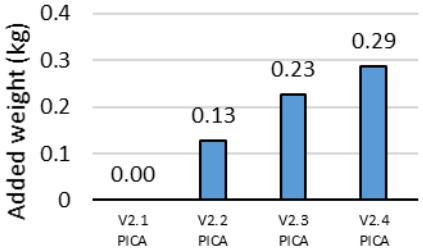





- **Latest CEA iterations look promising for meeting hard surface impact requirements**

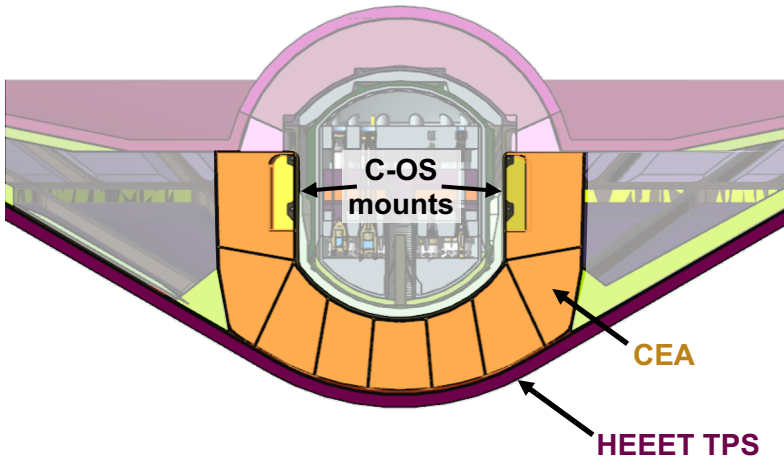
# HEEET TPS
## Some Considerations for Stiff/Structural TPS



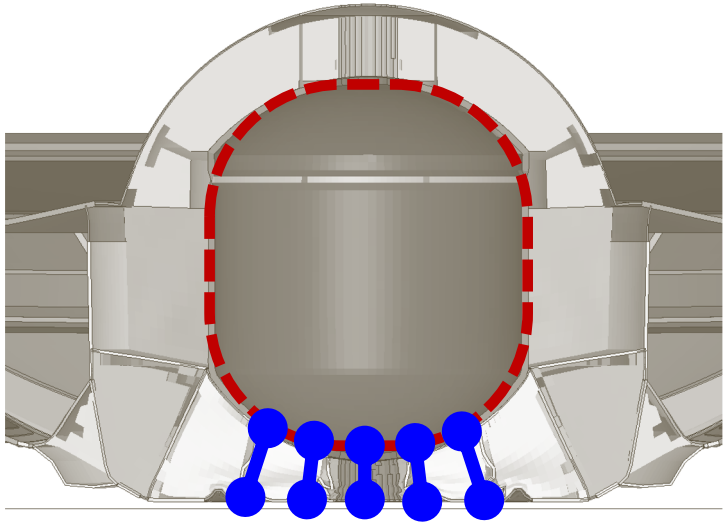
1. **Stiff TPS could prevent CEA crushing**
   - Instead, loads could pass through outer webs and fail the C-OS mounts, which would be unacceptable

2. **Thick structural TPS could interact with the CEA in an unforeseen negative way**
   - Example: TPS could bunch/mushroom around nose, leading to premature C-OS loading

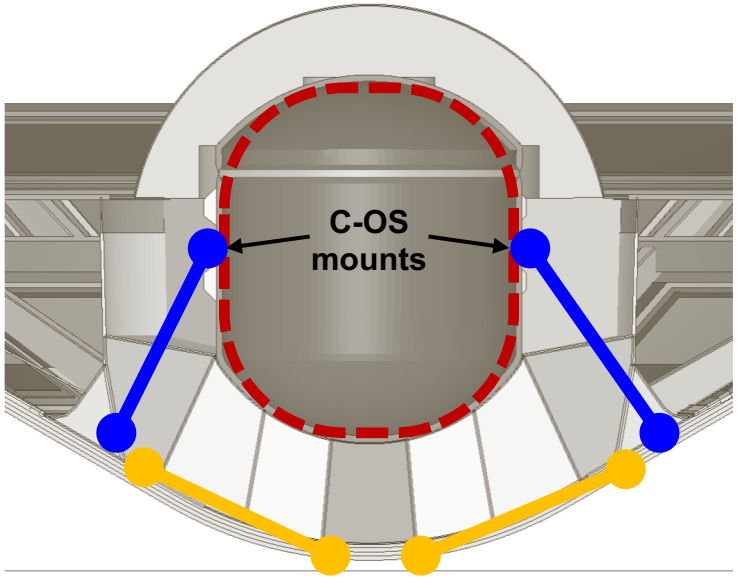
3. **On the other hand, HEEET layer(s) could absorb significant energy, assisting with off-nominal impact**




**Desired load path**

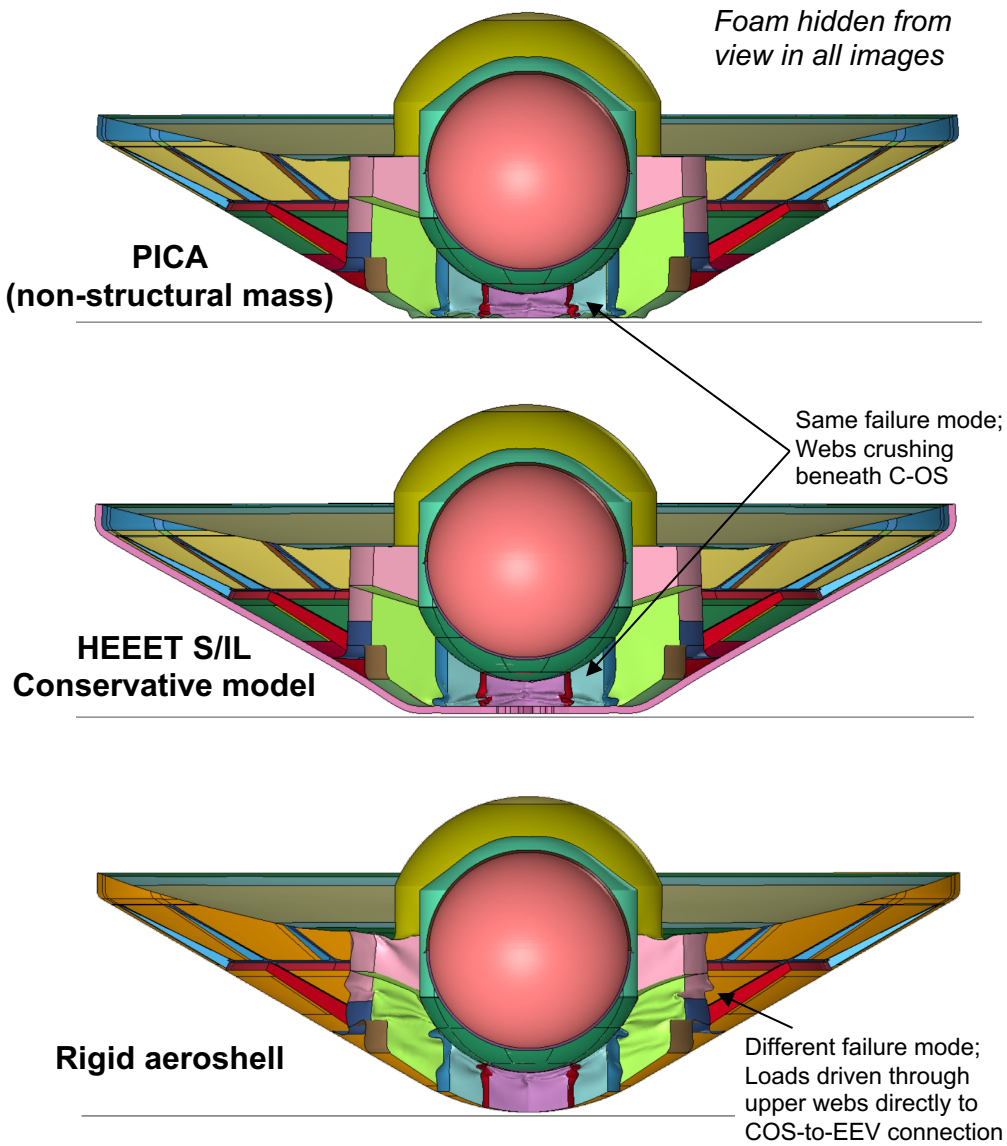


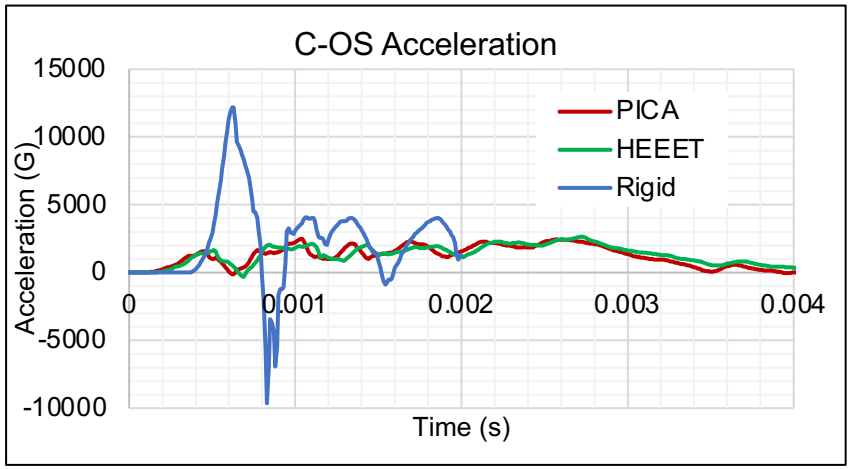
**Undesired load path**



# HEEET TPS – Effect On CEA Crushing
## Bounding Analyses





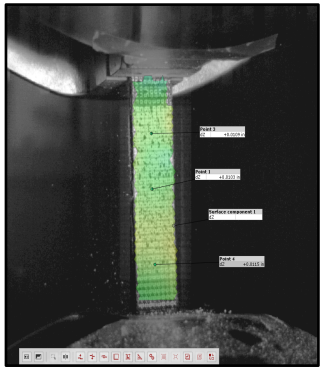

- **Bounding analyses (old EEV design)**
  1. PICA EEV model
     - Baseline / lower bound model
  2. Conservative HEEET IL model
     - Tensile failure, no compressive failure
     - More elastic (i.e. stiffer) than actual material which would have compressive damage
  3. Rigid aeroshell
     - Upper bound model

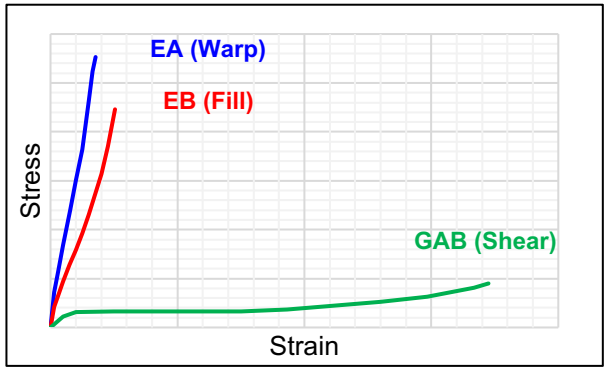
- **Conclusion: HEEET will not prevent energy absorber from crushing as desired**
  - Addresses consideration/concern #1
  - <u>To address considerations #2 and #3, need to model HEEET and analyze EEV impact</u>

# HEEET IL
# Initial Model Inputs Derived from Test Data

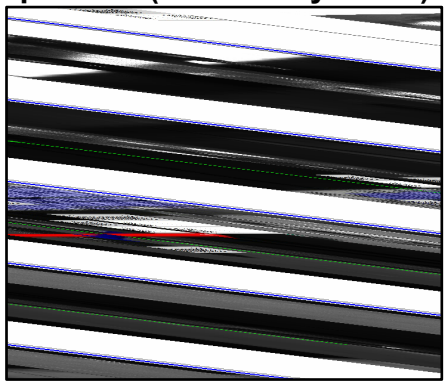


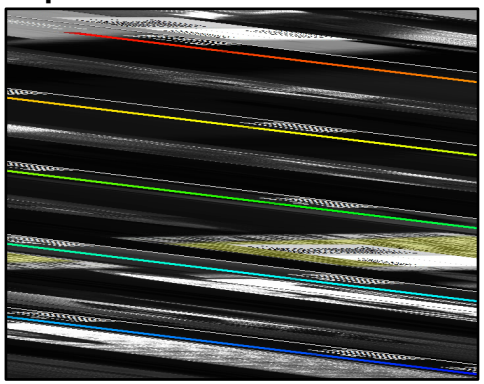
**Static Tensile Coupons**



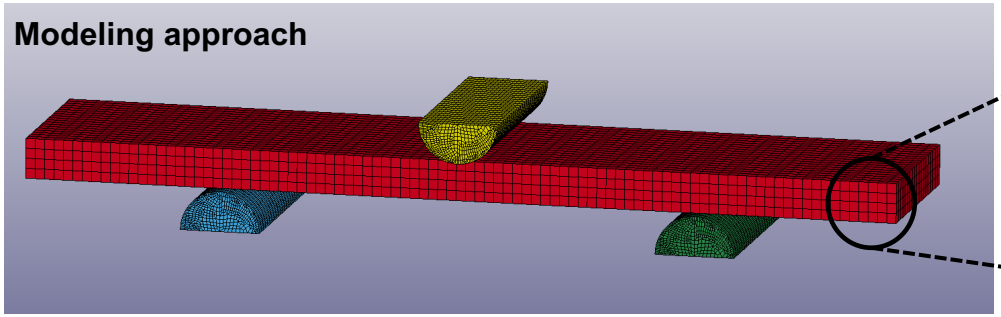


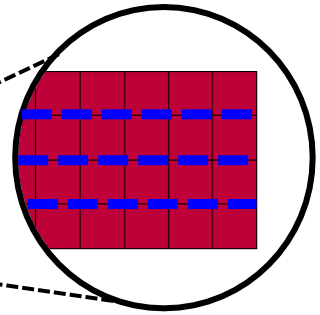

**3pt Bend (Static & Dynamic) Coupons**

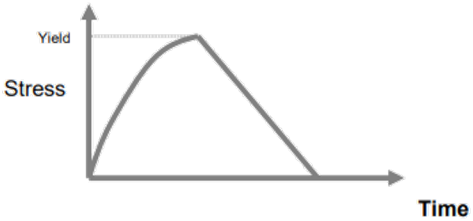




**Modeling approach**





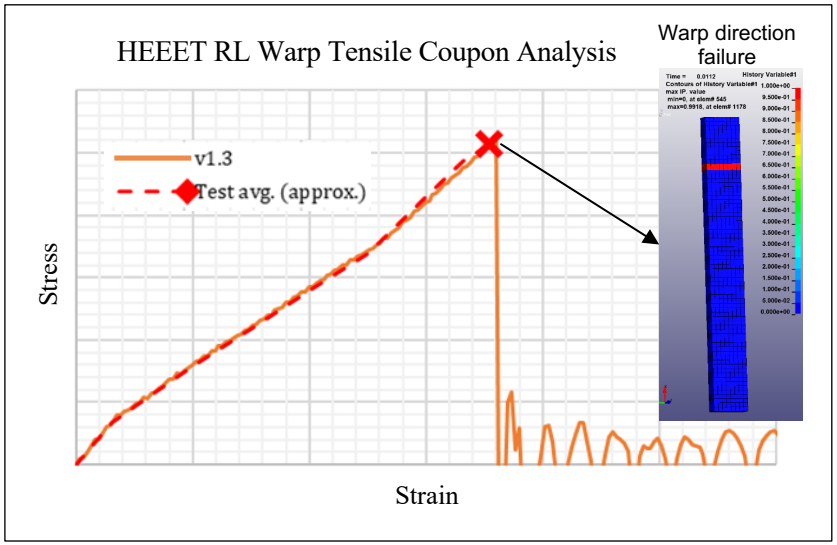


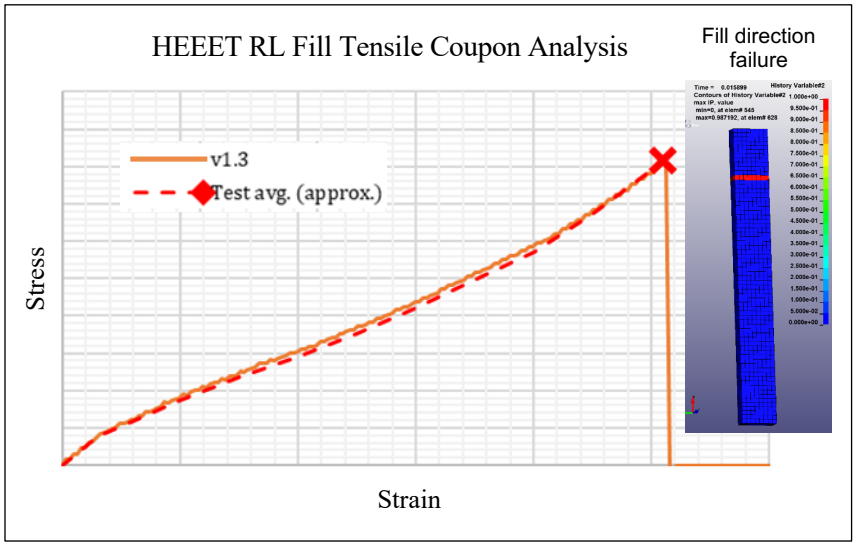

Stress Profile

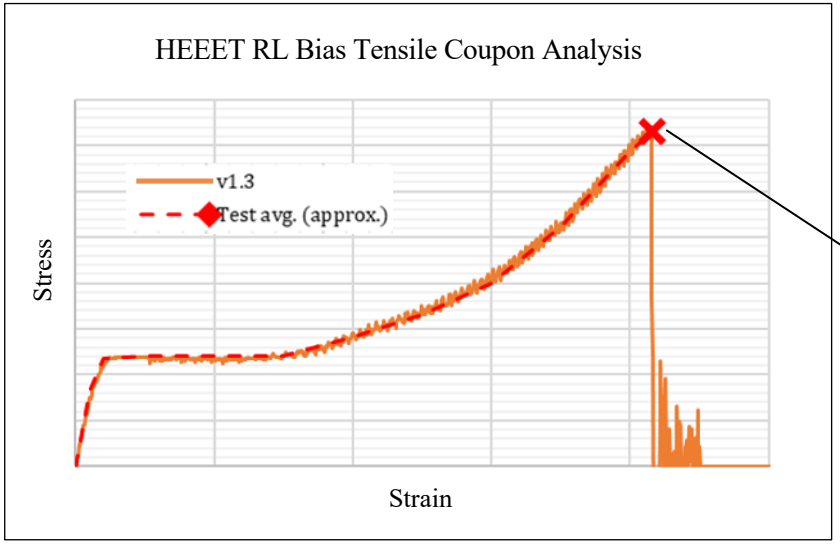
# HEEET IL Model Development

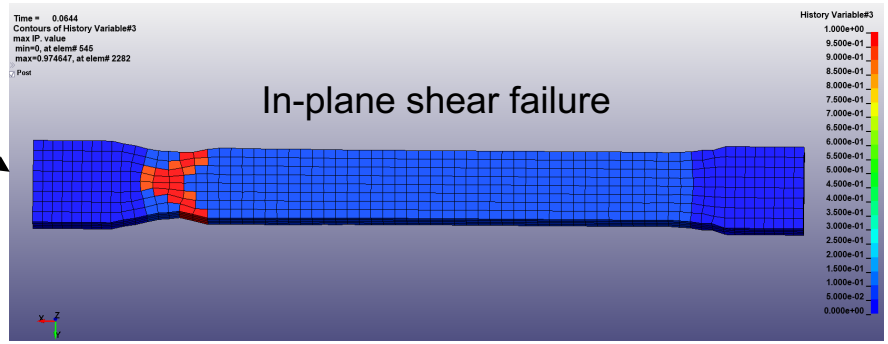
## Tensile Coupon Testing





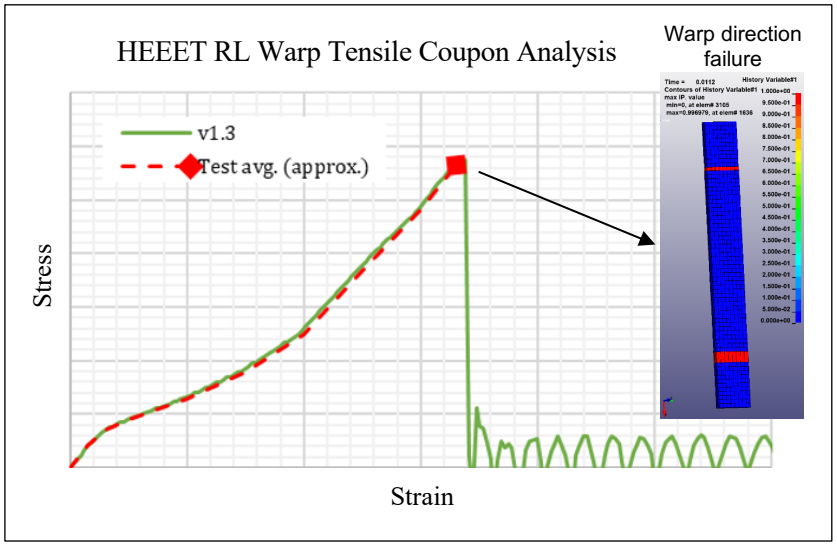



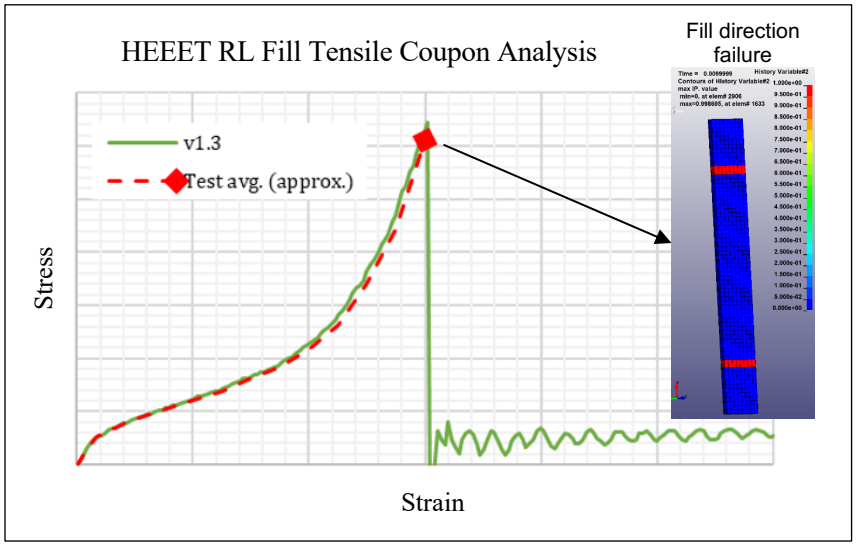



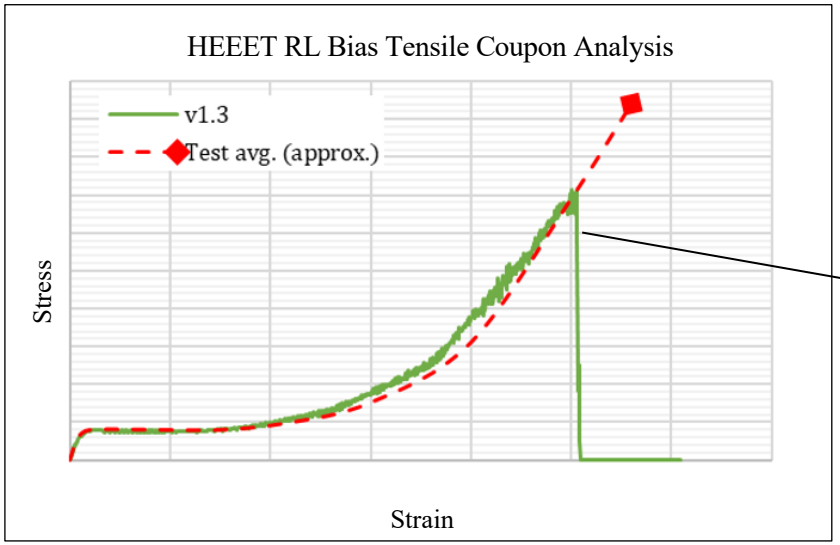



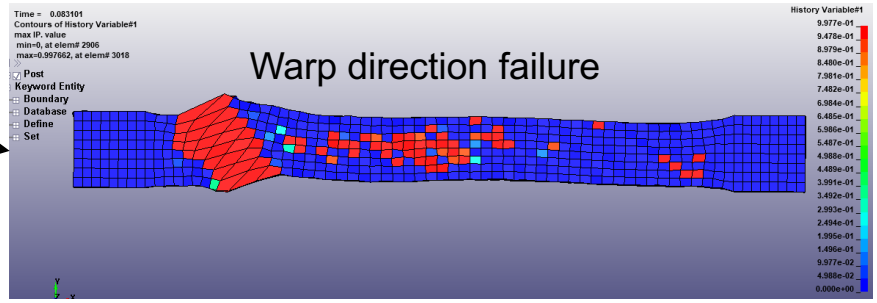
# HEEET RL Model Development
## Tensile Coupon Testing





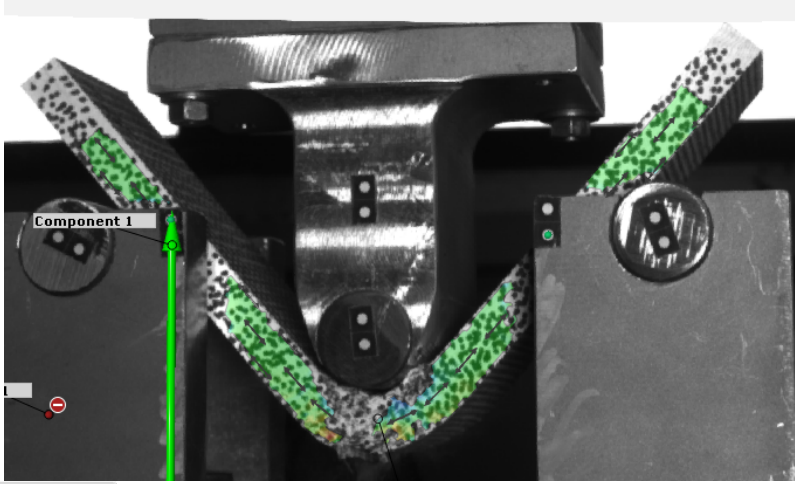



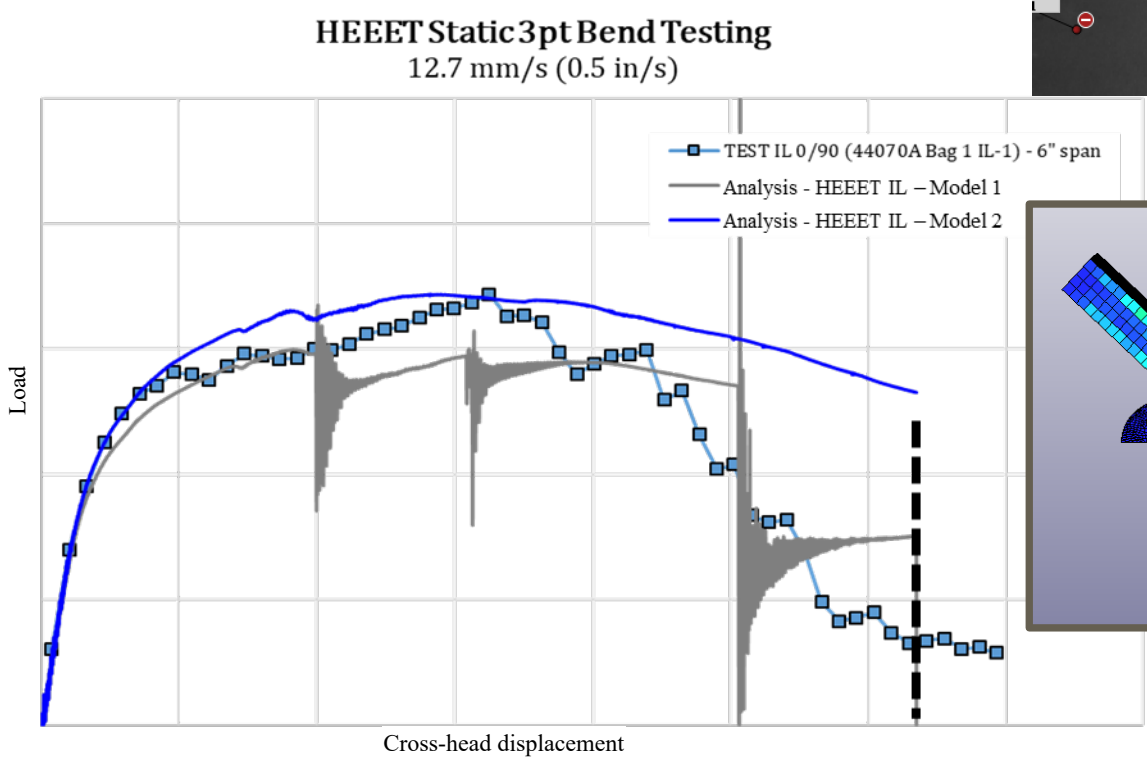



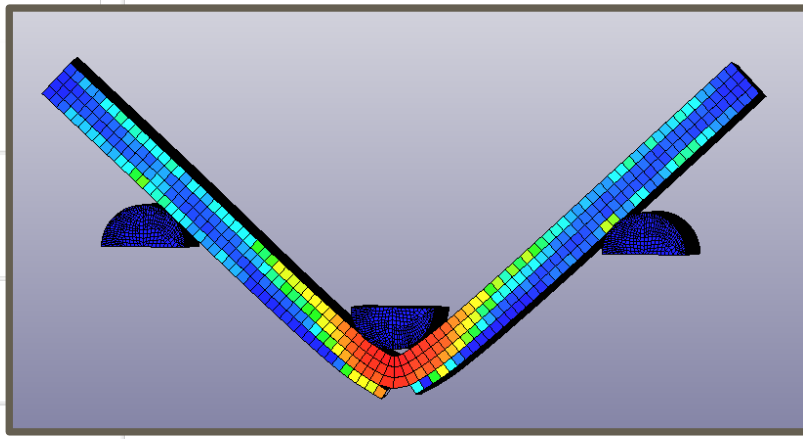
# HEEET IL Model Development
## Wide Span Dynamic 3pt Bend Testing



- **Goal: Match energy absorbed, load history, and deflection profile**
- **Results: Peak loads and deflections are on the right order, but energy absorbed may be over- or under-predicted depending on support span**



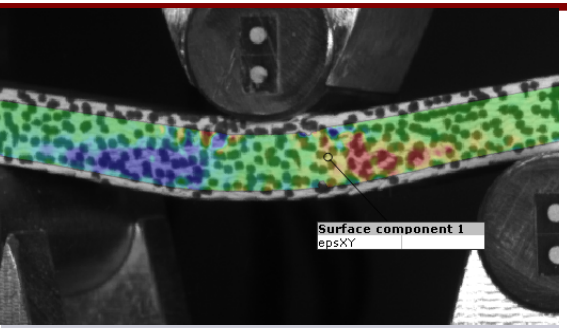



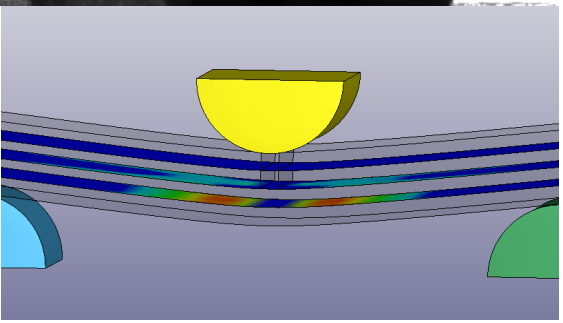



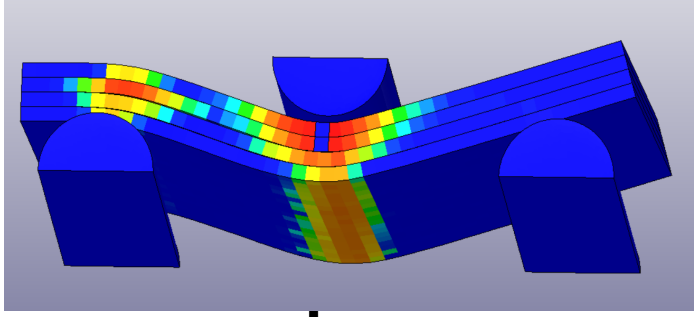
# HEEET IL Model Development

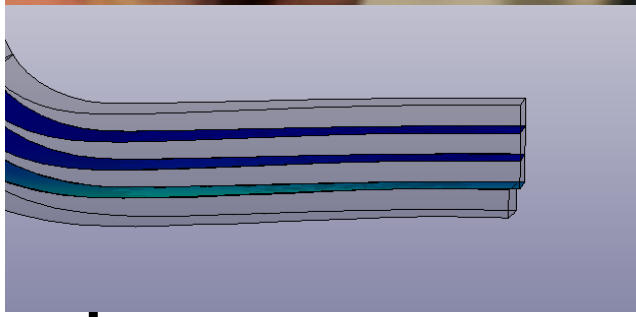
## Short Span Dynamic 3pt Bend Testing

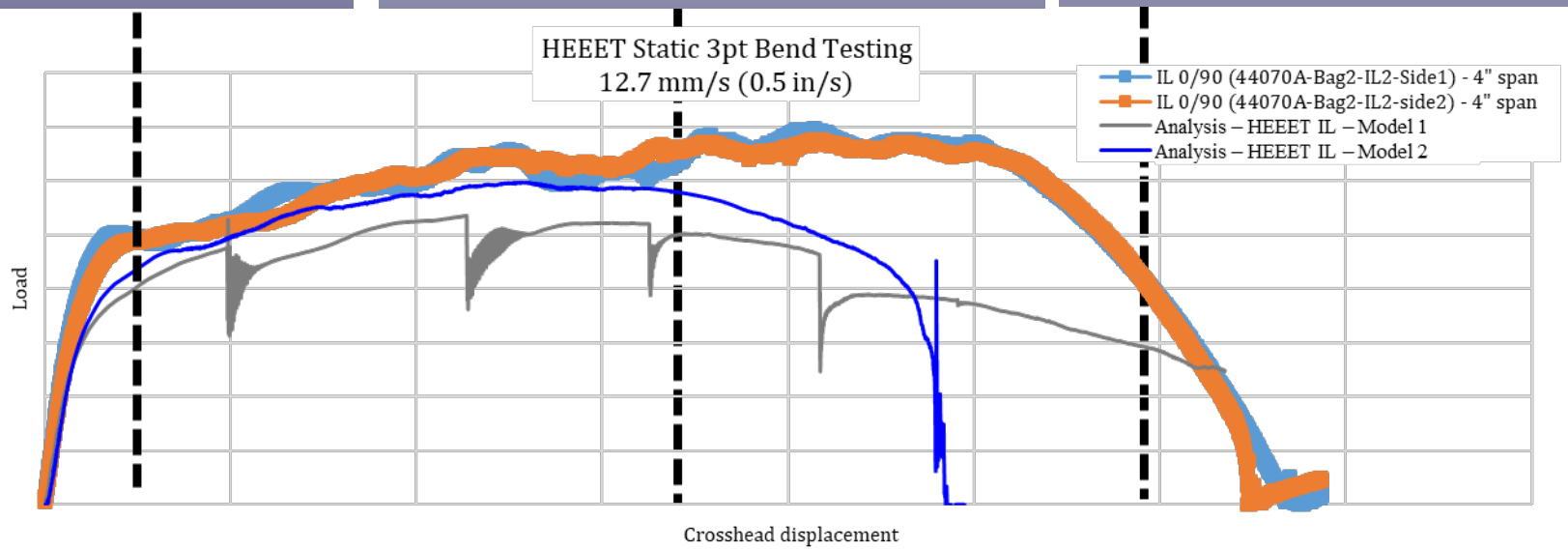








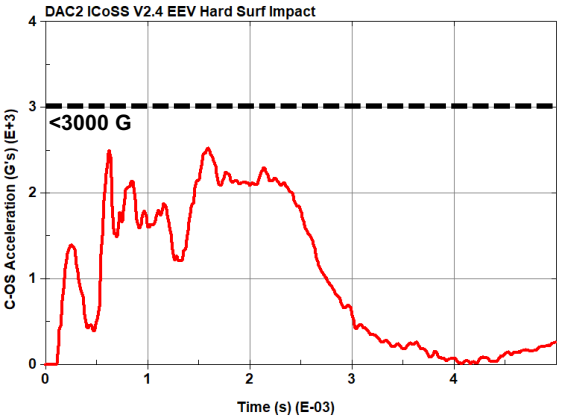


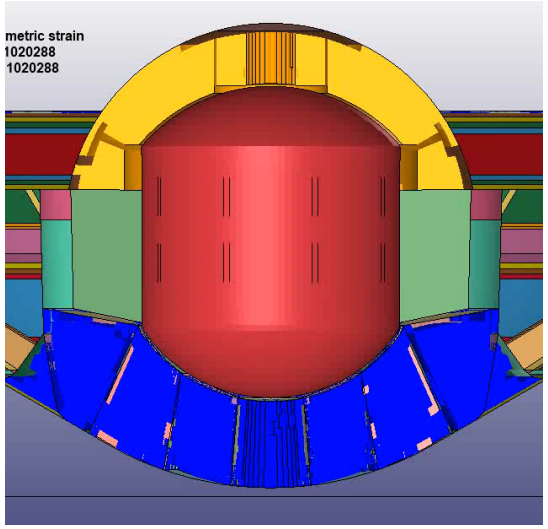


# CEA Web Pattern and Layup Iterations
## Hard Surface Impact – PICA vs. HEEET

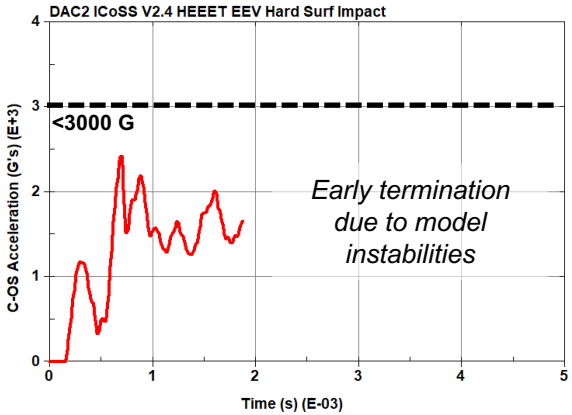


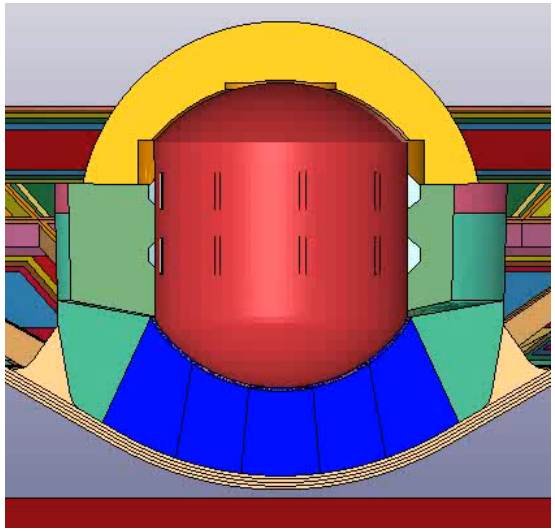
### PICA EEV



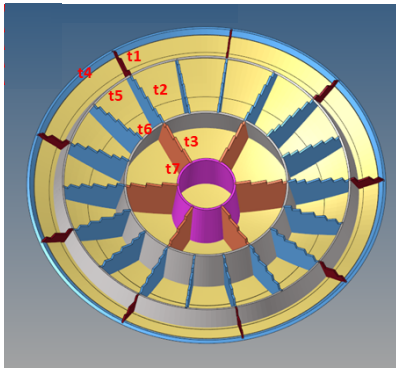




### HEEET S/IL EEV



V2.4: Added more webs (t2) to outer hoop




- **Initial hard surface impact results for HEEET TPS are encouraging**
  - Results before premature model termination suggested equivalent or lower C-OS loads with HEEET vs. PICA
  - No apparent bunching, inward ingression, or other negative interaction with CEA
  - Material model is still too immature to be conclusive, though; further development and/or testing is needed

# Conclusions and Future Work



- Testing and corresponding analyses for developing validated EEV off-nominal impact models via a building block approach are progressing
- Analyses of latest CEA design iterations with models developed thus far are encouraging for meeting C-OS loading and CEA crush margin performance metrics
- HEEET will not prevent proper crushing behavior of the CEA
- Initial hard surface impact results for HEEET TPS suggest similar or possibly lower loads compared to PICA
  - Further development and possibly testing is needed to confirm HEEET behavior
- Future/on-going work
  - Continue CEA element testing and model validations
  - Utilize Quantification of Margins and Uncertainties (QMU) approach, particularly to quantify modeling uncertainties

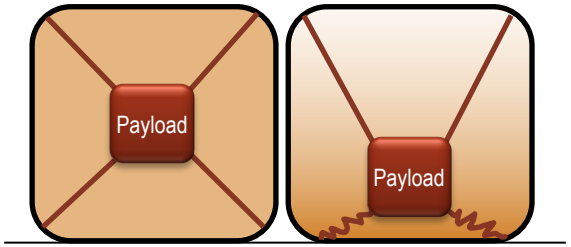
# BACKUP

# Energy Absorber Design Architecture



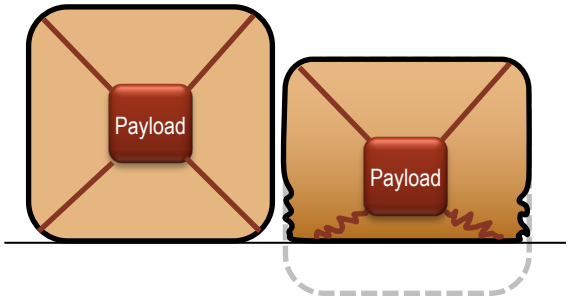
**Two major classes of blunt impact energy absorber architectures considered:**

## "Shock Absorber" Architecture

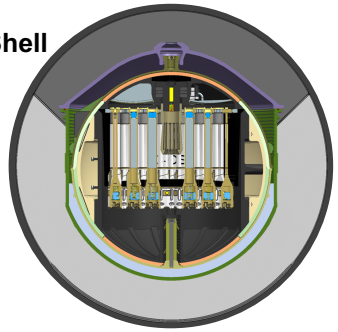


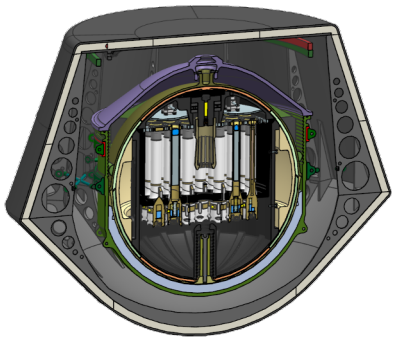

- Energy is dissipated by internal energy absorber (crushables, plastic deformation, etc.)
- Need large stroke energy absorber that doesn't de-couple the payload from the structure
- Exterior structure deforms very little
- **Therefore, external structure must be very stiff and strong → Heavy design**

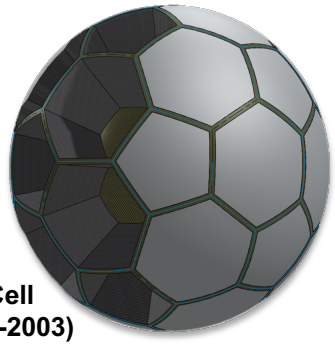
## "Crumple Zone" Architecture

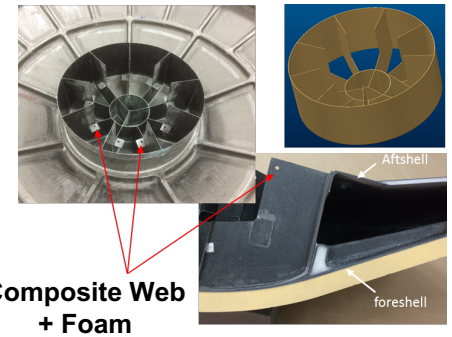



- Energy is dissipated by deformation and failure of the structure itself
- Material ahead of payload absorbs impact energy
- Structure adjacent/behind the payload remains intact and maintains coupling with the vehicle
- **Lower mass option; approach chosen for the EEV CAM**



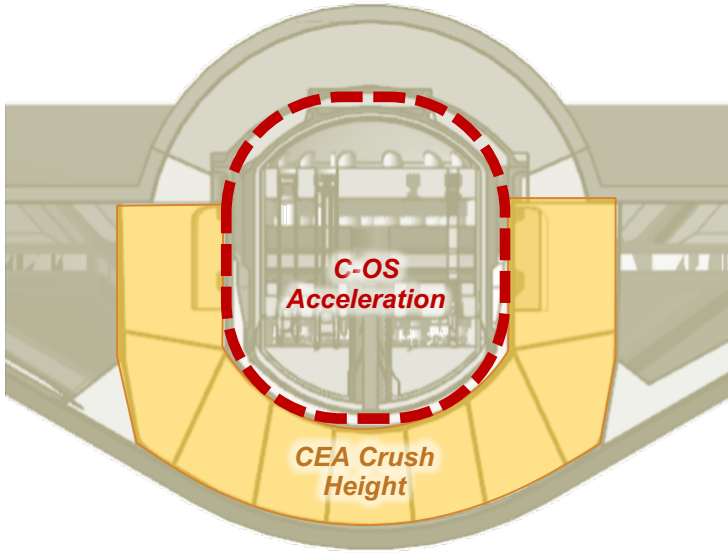



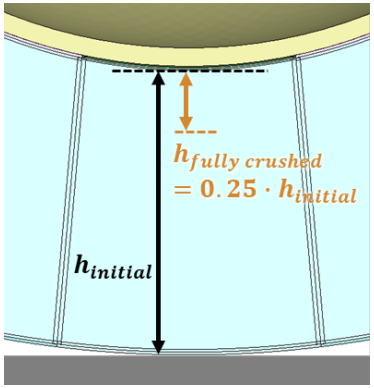



# Off-Nominal Impact Performance Metrics

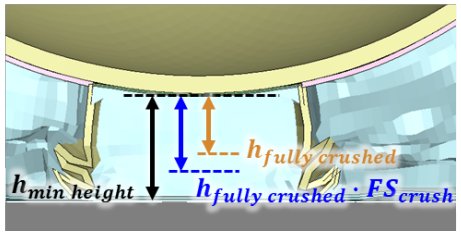


- **Current metrics in use:**
  - **C-OS Loading**
    - In-direct measure of containment failure
    - Loads defined at the CAM/C-OS interface
    - Estimate C-OS can be designed to withstand 3000 G
      - Design, analysis, and testing is being conducted in FY19 to verify
  - **CEA Crushed Height**
    - Fully crushed material is stiff and hard to characterize
      - Loads increase drastically
      - FE models are also likely unreliable
    - Estimate 75% stroke efficiency
    - Therefore, fully crushed height is 25% of initial; apply safety factor




$$MS_{crush} = \frac{h_{min\ height}}{h_{fully\ crushed} \cdot FS_{crush}} - 1$$

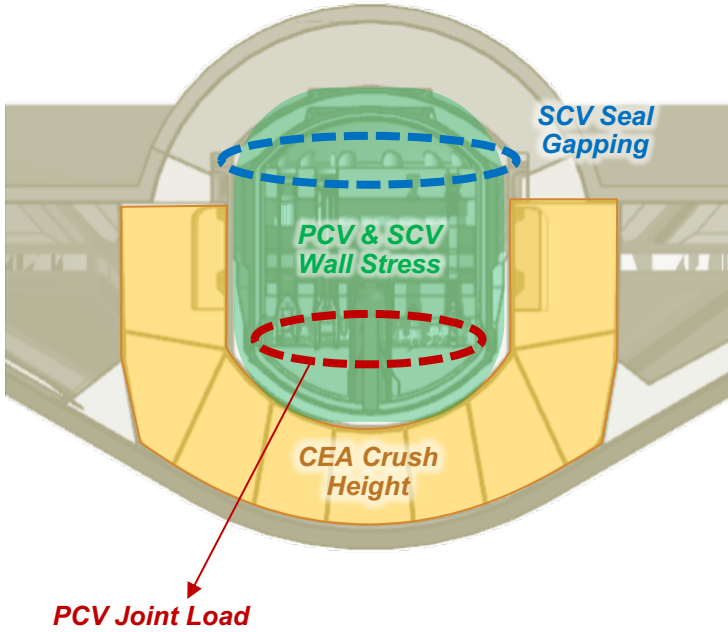


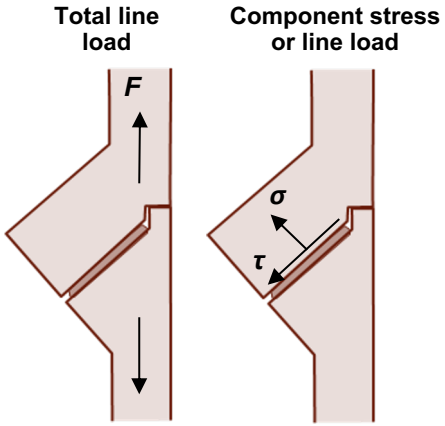

| Metric | Allowable | F.S. |
|---|---|---|
| 1. C-OS Loading | 3000 G | 1.0 |
| 2. CEA Crushed height | 25% | 1.3 |

# Off-Nominal Impact Performance Metrics



- **Eventual goal: Develop metrics and models for predicting SCV and PCV failure**
  - Direct measures of whether containment has been maintained or not
  - Longer-term effort requiring dynamic/impact testing of container articles and corresponding model development to establish reliable metrics and analytical approaches
    - *(Also tasks I am working)*

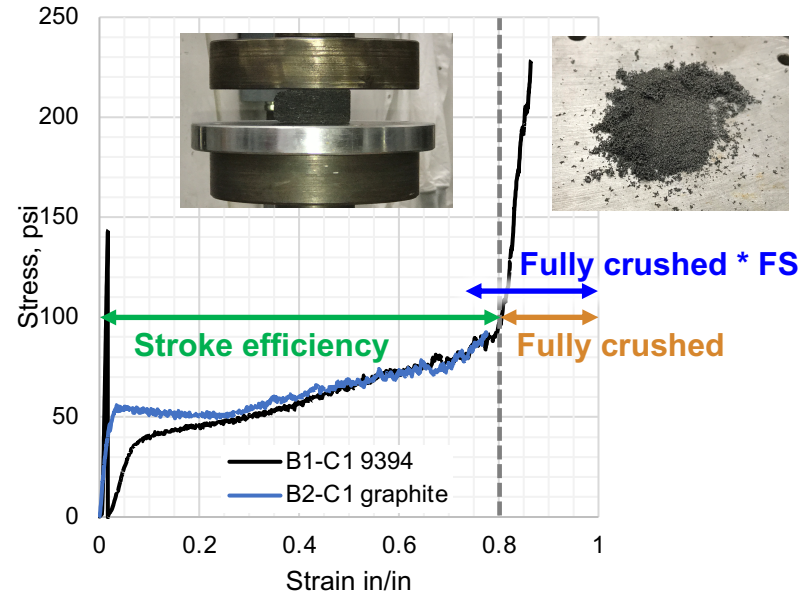


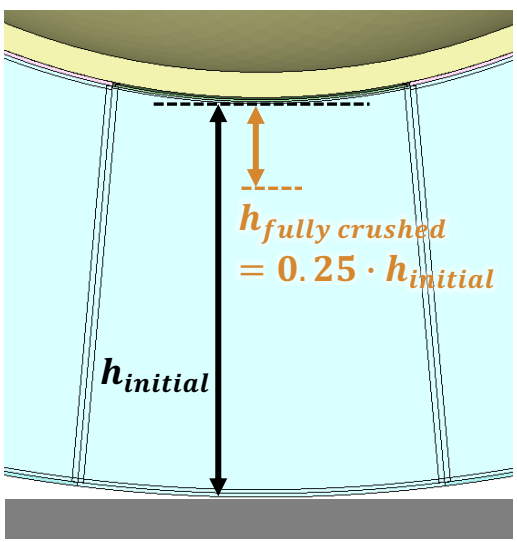



# CEA Crushed Height Metric

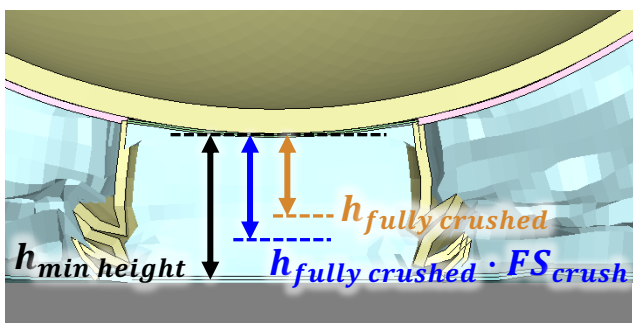


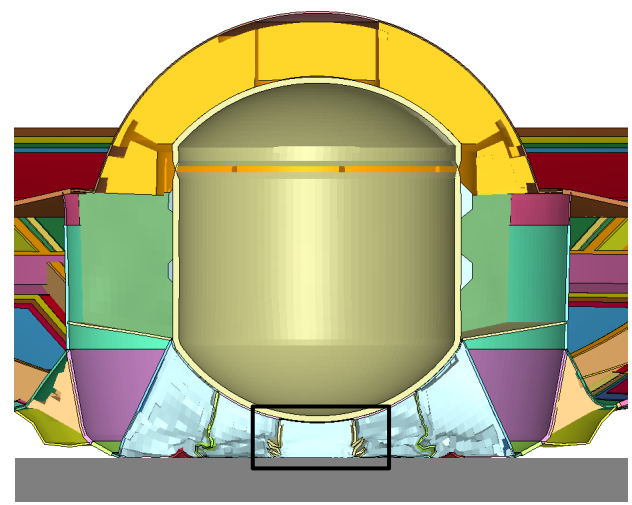
- **Avoid crushing CEA beyond its stroke efficiency**
  - Fully crushed material is stiff and hard to characterize
    - Loads increase drastically after this point
    - Models also become unreliable after this point
  - Estimate 75% stroke efficiency for CEA structure
  - Therefore, fully crushed height is 25% of initial
  - Use 1.3 factor of safety to provide buffer



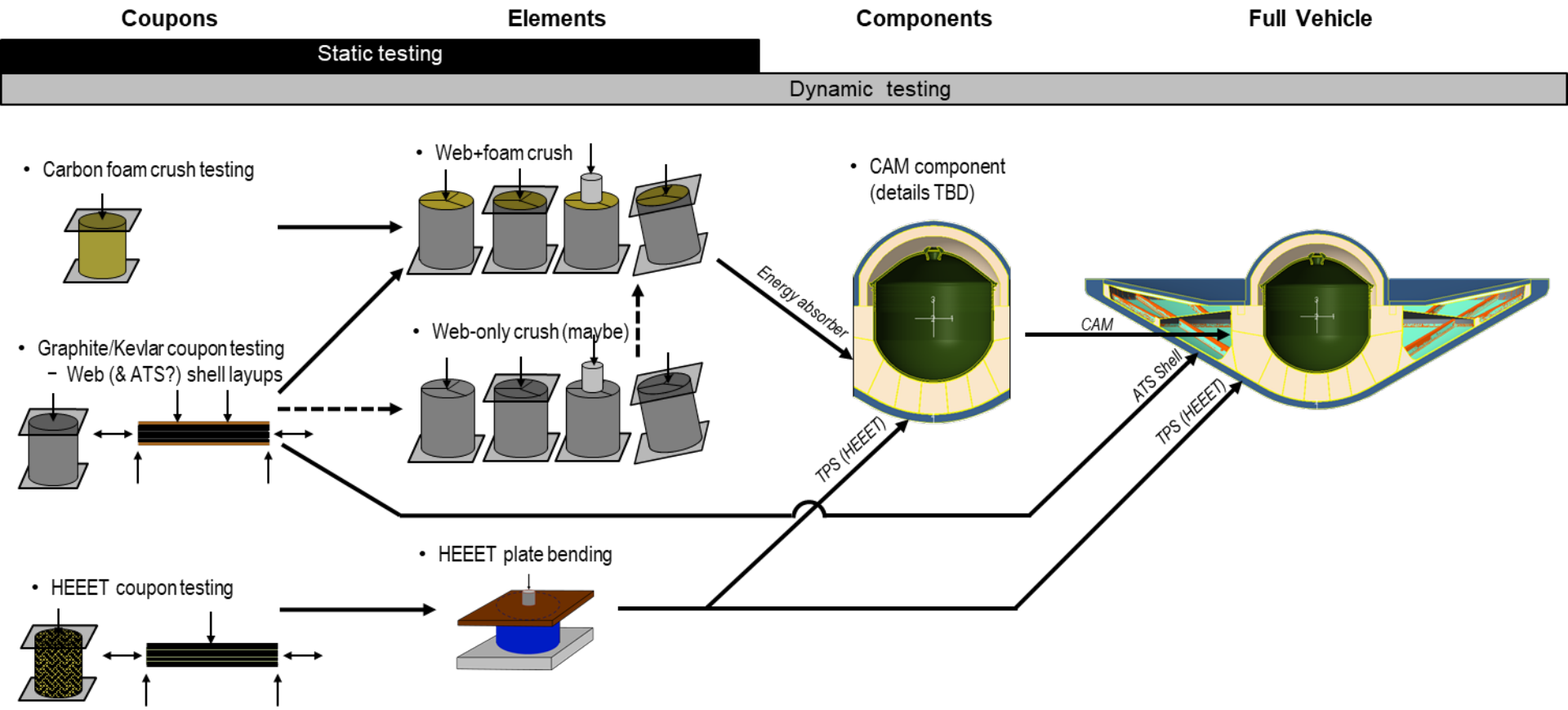

$$MS_{crush} = \frac{h_{min\ height}}{h_{fully\ crushed} \cdot FS_{crush}} - 1$$



# CEA Modeling for Impact
## Building Block Approach






$$MS_{crush} = \frac{h_{min\ height}}{h_{fully\ crushed} \cdot FS_{crush}} - 1$$

# DAC2 Off-Nominal Landing Cases

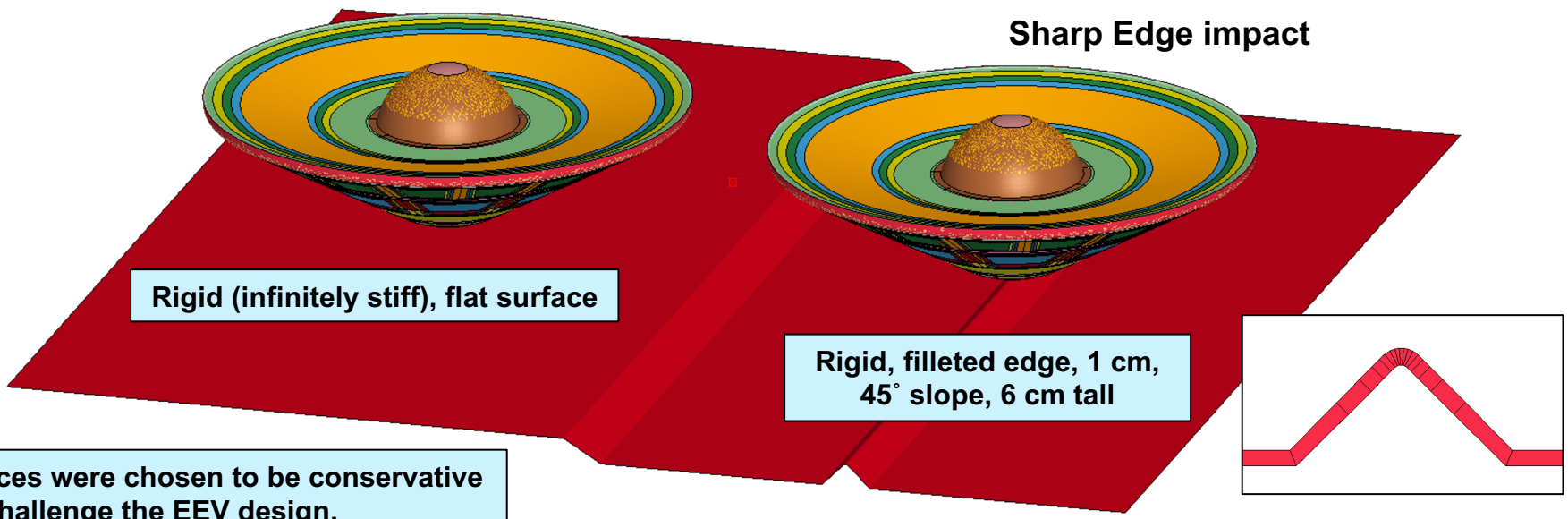


**Potential Off-Nominal Impact Cases**

| | |
|---|---|
| **Case 1: Soft Surface**<br>• High surface normal velocity<br>• Dry hard soil, all layers<br>• High AoA on sloped ground | **Case 2: Hard Surface**<br>• High surface normal velocity<br>• Rigid, flat surface<br>• AoA relative to surface |
| **Case 3: Sharp Edge**<br>• High surface normal velocity<br>• Rigid filleted edge:<br>1 cm / 45˚, 6cm tall | **Case 4: Inverted**<br>• Low normal velocity<br>• Rotational velocity relative to CG |

**Hard Surface impact**

**Sharp Edge impact**



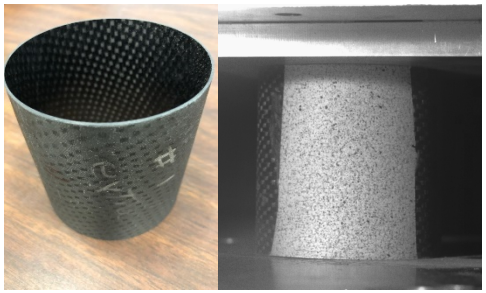

**Surfaces were chosen to be conservative and challenge the EEV design.**

# CEA Material Model Development
## LS-DYNA Mat58

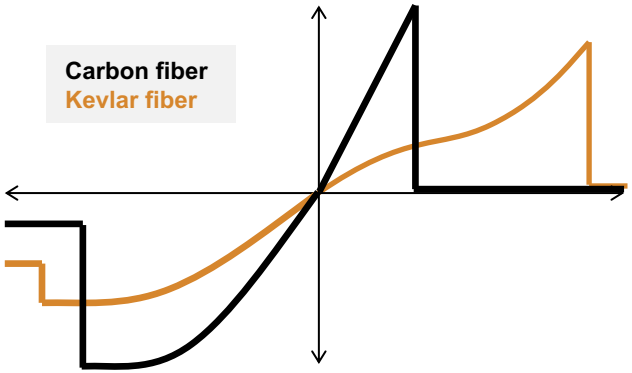


- **Orthotropic model with direction-dependent failure; Suitable for both carbon and Kevlar composites**
- Arbitrary stress-strain response can be defined for $E_A$, $E_B$, $G_{AB}$, both in the tension and compression
- Post-damage response can capture complete loss of load carrying capability (appropriate for tensile failure) or sustained a load/stress carrying capability after failure (appropriate for compression and shear failure)

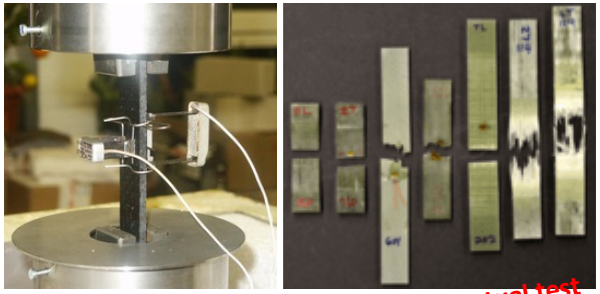
**(0/90) fabric layup compression cylinder coupons**



**Mat58 Custom $E_A/E_B$ S-S Response**

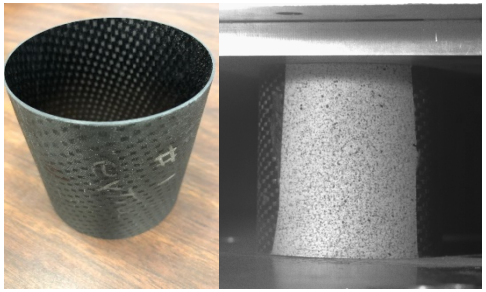



**(0/90) fabric layup tensile coupons**

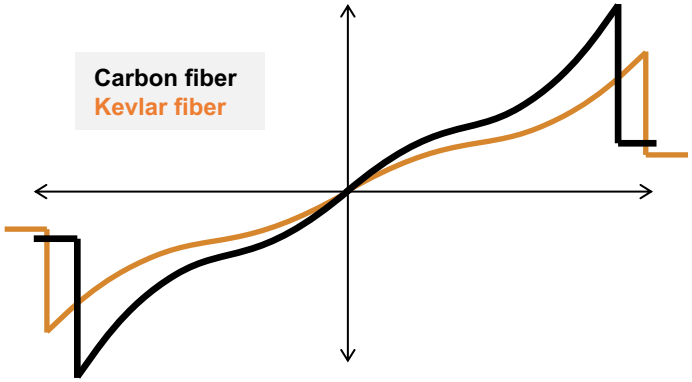


Replace with actual test pics or better graphic

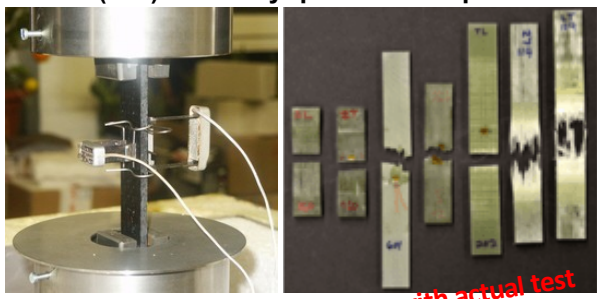
**(±45) fabric layup compression cylinder coupons**



**Mat58 Custom $G_{AB}$ S-S Response**




**(±45) fabric layup tensile coupons**



Replace with actual test pics or better graphic