Best Practices for Verifying and Validating Complex Non-Linear Finite Element Models of Concrete Structures

Robert MacNeill
Associate Principal, Simpson Gumpertz & Heger Inc., 480 Totten Pond Road, Waltham, MA 02451, USA
Tel: (781) 907-9481, email: ramacneill@sgh.com

Robert MacNeill, P.E.

- Associate Principal, Simpson Gumpertz & Heger (SGH)

- 28 years of engineering experience
  24 as an engineering consultant
  4 in aerospace

- Education:
  BS/MS Mechanical Engineering, RIT, 1995
  Grad studies, Aero/Astro Engineering, Stanford 1995/1996

- Areas of Expertise:
  Nonlinear dynamic finite element analysis (FEA), with LS-DYNA
  Impact, blast, and failure analysis
  Transportation safety (rail vehicle design, crashworthiness, aircraft impact)
  Test design and implementation, including full-scale impact & blast testing

Outline

- Before You Start
  - Consider best approach
- Establish Methodology
  - Building up from basics
- Case Study: Aircraft Impact Analysis of Nuclear Powerplant
  - Putting it together in practice

Before you Start: Consider What the Model Needs to Do

- Consider how accurate or conservative the answer needs to be for the problem

  Will hand calcs and simplified methods suffice?
- Most efficient

  Looking to ensure something meets requirements
- Some simplifying assumptions can be made

  Looking for precision (within X% of actual response)
- A well-characterized methodology is needed. Most complex

Before you Start: Consider What the Model Needs to Do

- Consider Scale Needed:

  Fine Detail: Modeling of aggregate and paste

  Normal Detail: Continuum of concrete with explicit rebar models

  Coarse Model: Smeared continuum of concrete and reinforcement

Before you Start: Consider What the Model Needs to Do

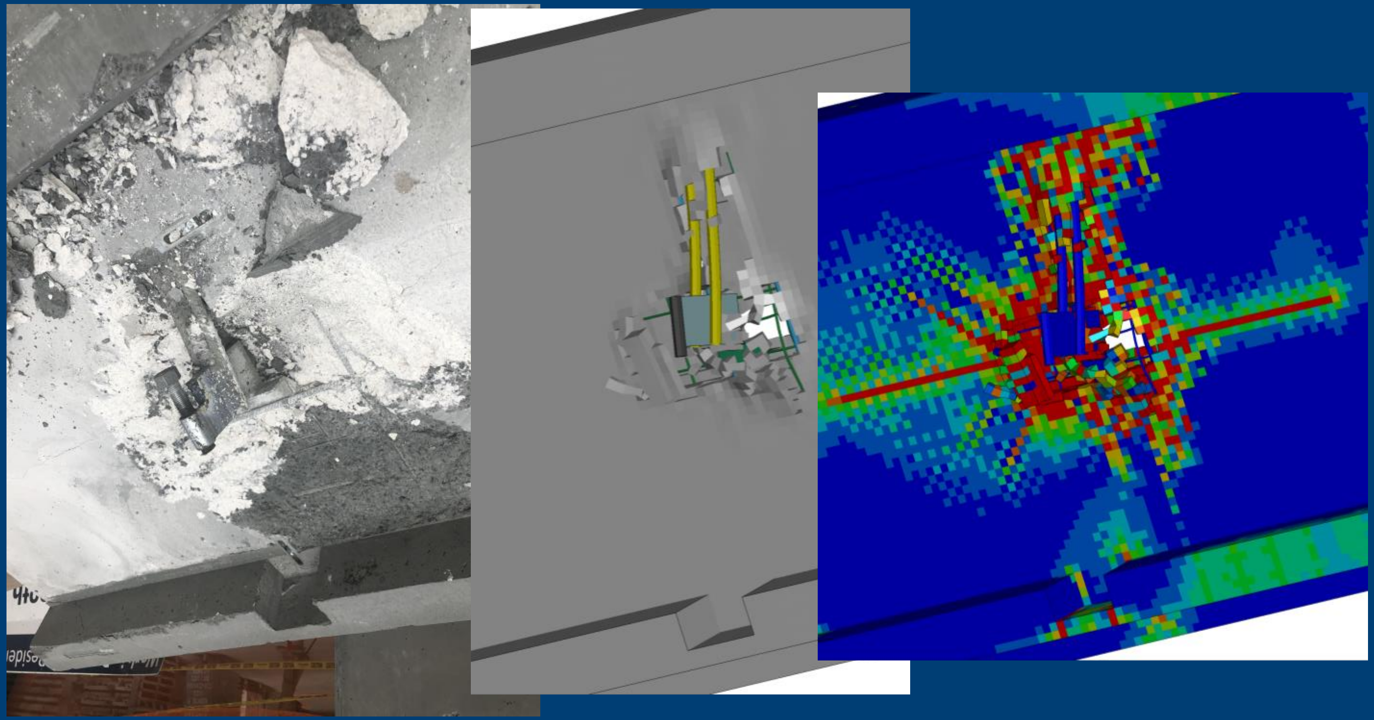
- Consider Anticipated Nonlinear Effects :

Concrete:

- Cracking
- Spalling, ejecta

Steel:

- Necking and Failure
- Bond failure
- High-rate loading (impact, blast)



Establish Methodology: Build up from Basics

- Single element tests
- Replicate material tests

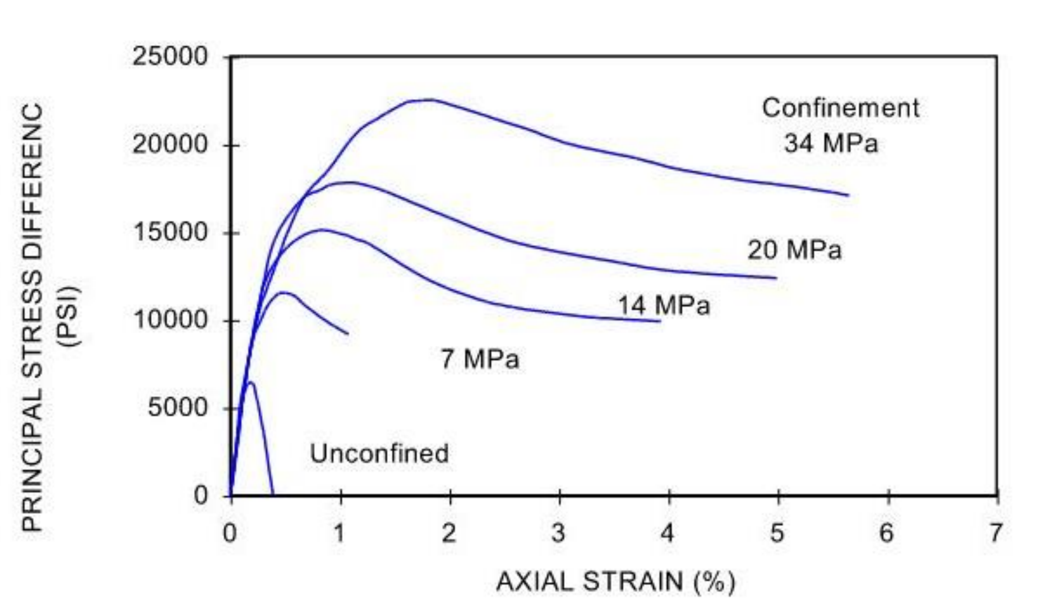
  Unconfined compression, split tensile, confined compression

  Tensile tests, split Hopkinson bar tests
- Subassembly or system level tests

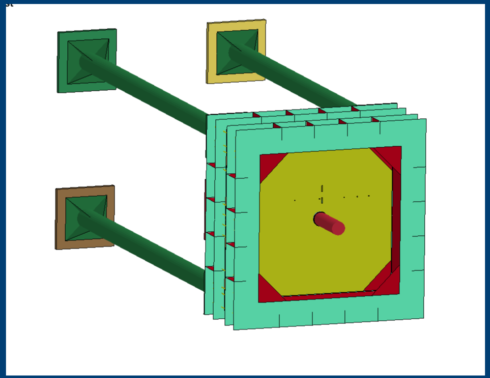
  compared to known response: model the test, closed-form solutions
- Methodology established: apply to real problems

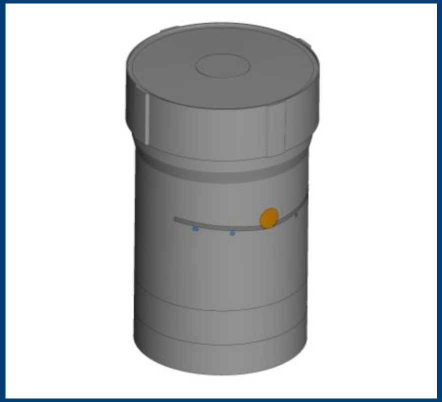
Establish Methodology: Build up from Basics

- Choose appropriate material constitutive models
  - Types of behavior needed
- Concrete—geomaterial models
- Steel Reinforcement—Plastic hardening models
- Choose models that can handle application requirements
  - Nonlinear models
  - Cyclic response—hysteretic behavior
  - Failure modeling
  - Thermal effects
  - Rate effects



Crawford, et al, Use & Validation of MAT72R3 in LS-DYNA, 2011





Case Study

AIRCRAFT IMPACT ASSESSMENT FOR NUCLEAR POWERPLANT STRUCTURES

Case Study: Establish Methodology for AIA for NPPs

- US CFR requires aircraft impact analysis (AIA) for all reactor and fuel storage structures at nuclear powerplants (NPP)
- Historically, this was done with hand calculations. Within the last 20 years, nonlinear FEA is typically employed
- We can not rely on full-scale testing to validate global models

Instead, we build up methodology from simple models to medium scale and validate along the way

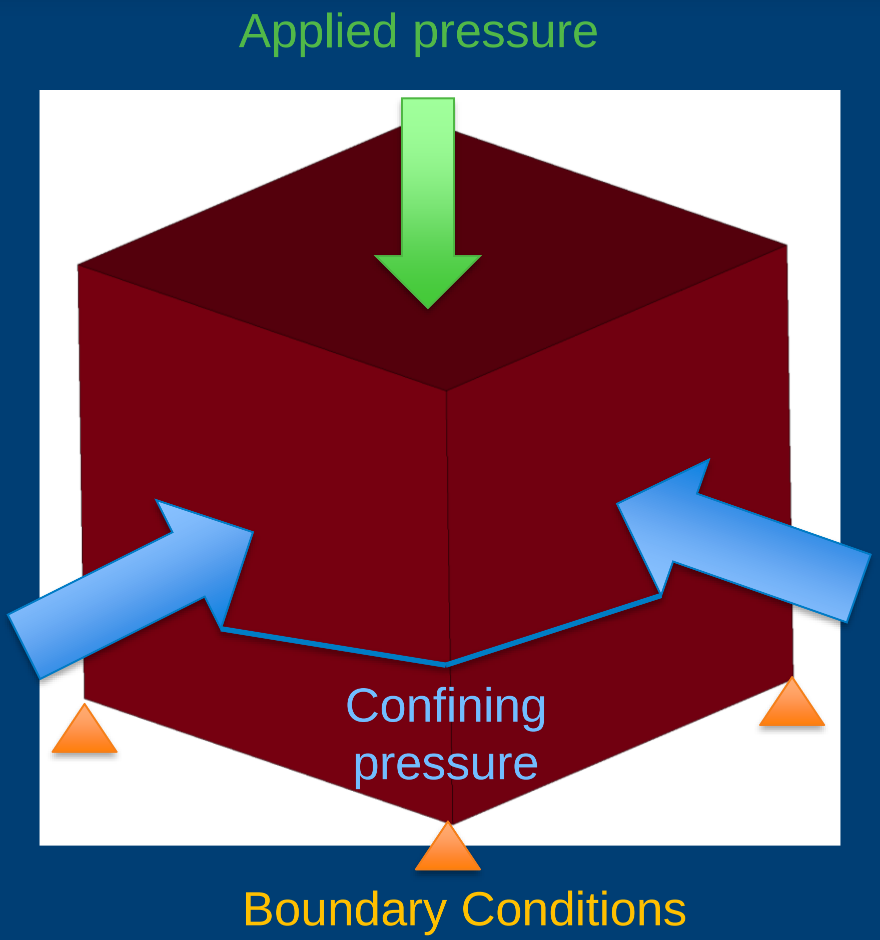
Material Model Calibration: Concrete

- Concrete material modeling
- Concrete nonlinear response is complicated and multivariable (e.g., material characteristics, loading environment)
- Model calibration can be

Simple: relying on simple inputs and extrapolations of underlying empirical inputs

→ less specific to the particular application

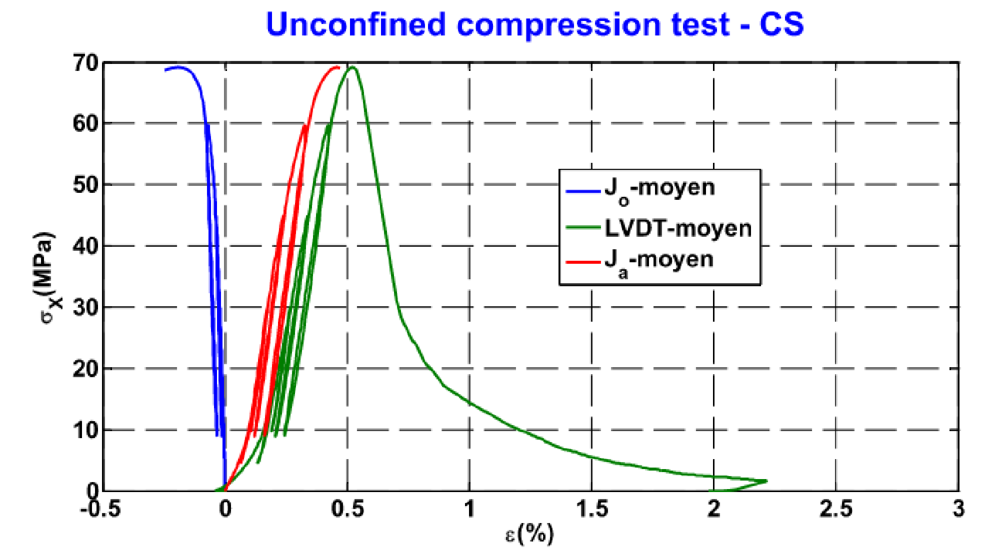
Complex: user calibration from material-specific characterization tests

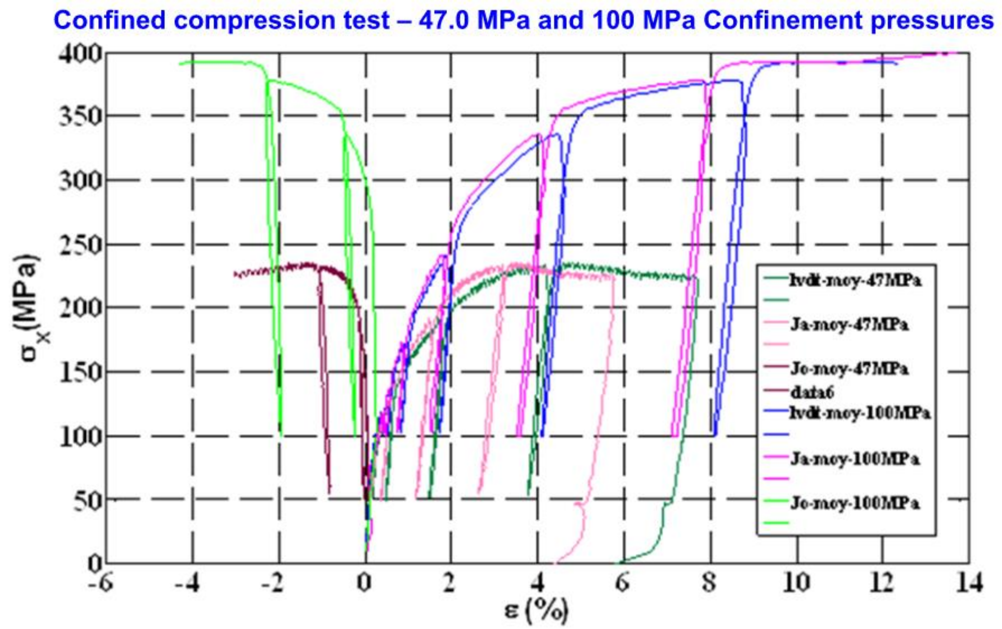


Material Model Calibration: Concrete

- Some factors to consider
  - Unconfined compression and tensile strength
  - Strength under variable confinement pressures
  - Strain rate strength dependency
  - Crack/Damage modeling
  - Hysteretic response
  - Mesh sensitivity

IRIS 2010 Experiments IRSN Test Results



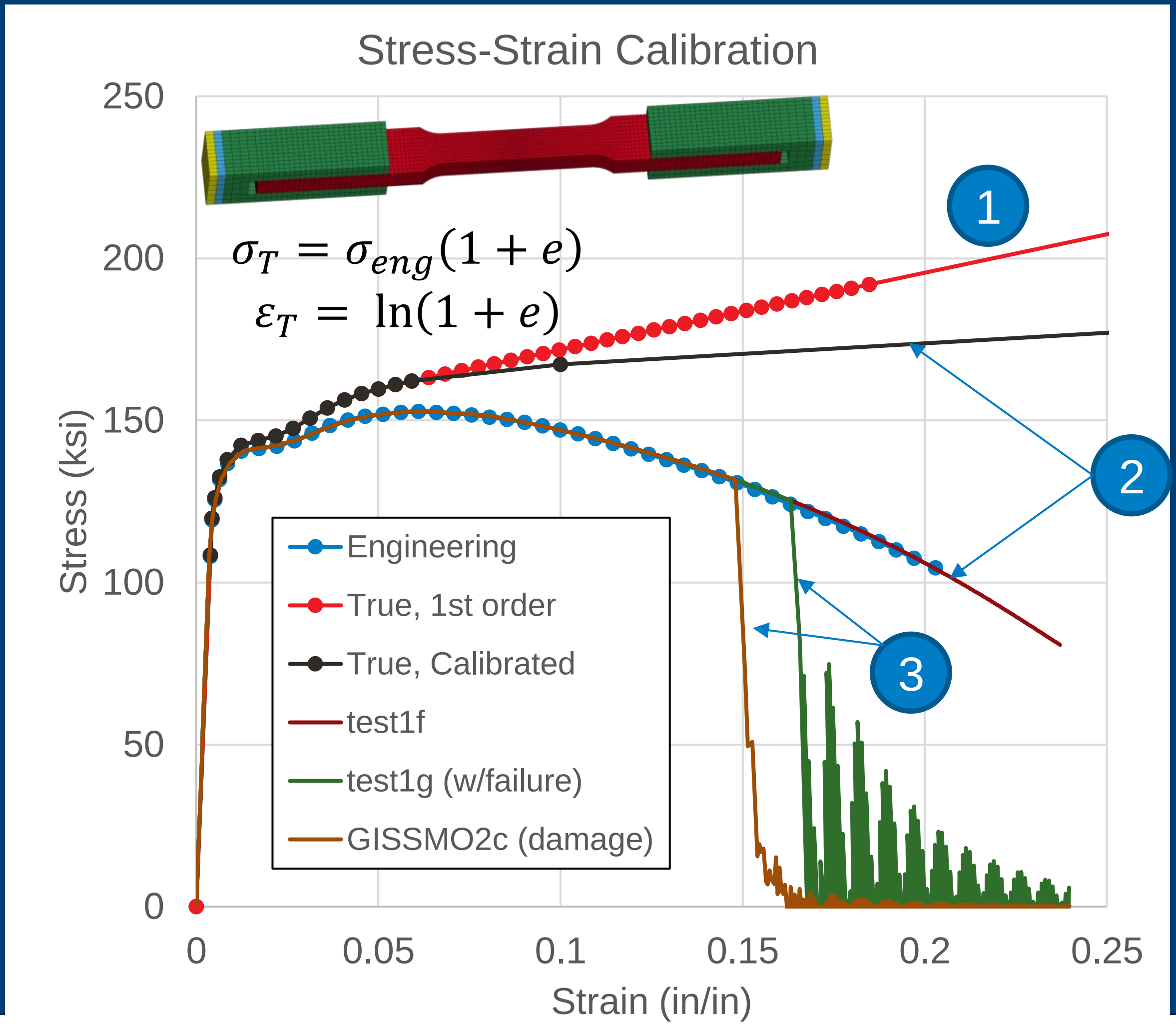


Loading-unloading cycles were carried out to determine evolution of Young's modulus.

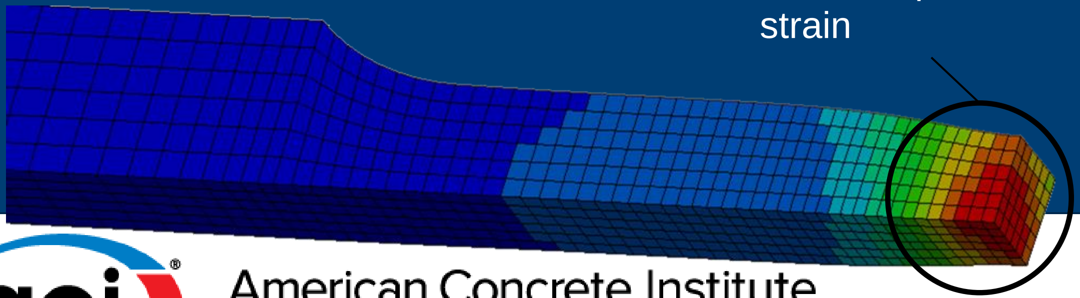
Material Model Calibration: Steel

- Material model was calibrated by replicating tensile test coupon. Basic Steps:
  1. Apply first-order corrections on published engineering stress-strain to estimate true stress-true strain curve
  2. Adjust post-necking points to replicate engineering stress-strain response with tensile test model (test1f)
  3. Add failure models to calibrated material model
- Option A: Critical strain for element erosion (test1g)
- Option B: Stress triaxiality-based damage and failure model (GISSMO2c)

  Used for bolt failure analysis



Tensile Test Model Example

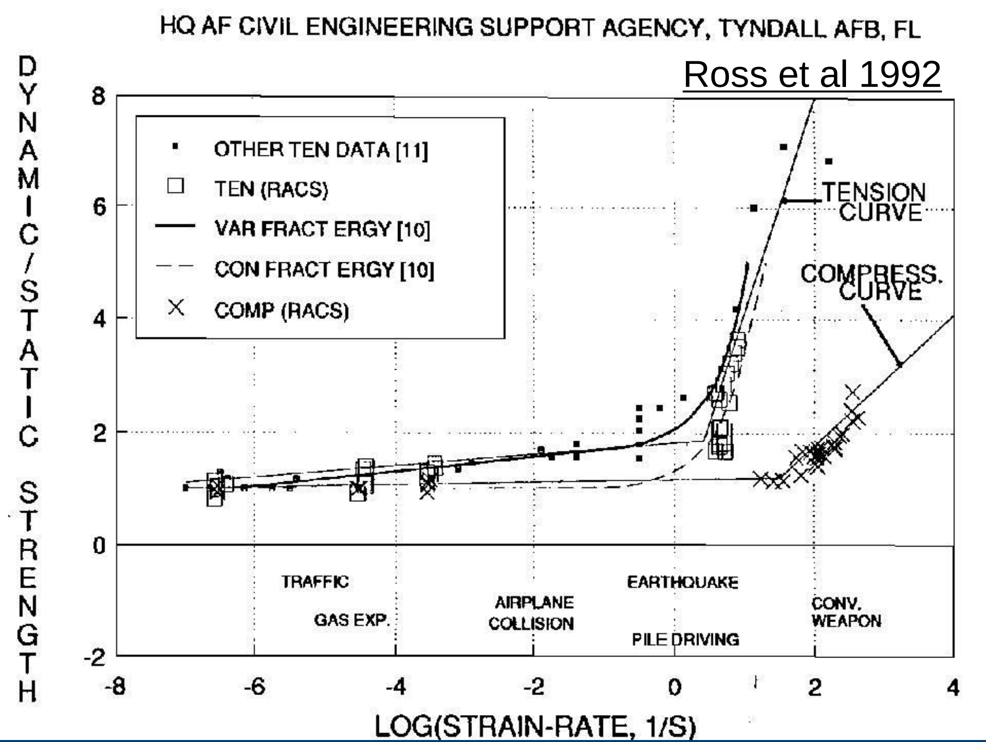


American Concrete Institute

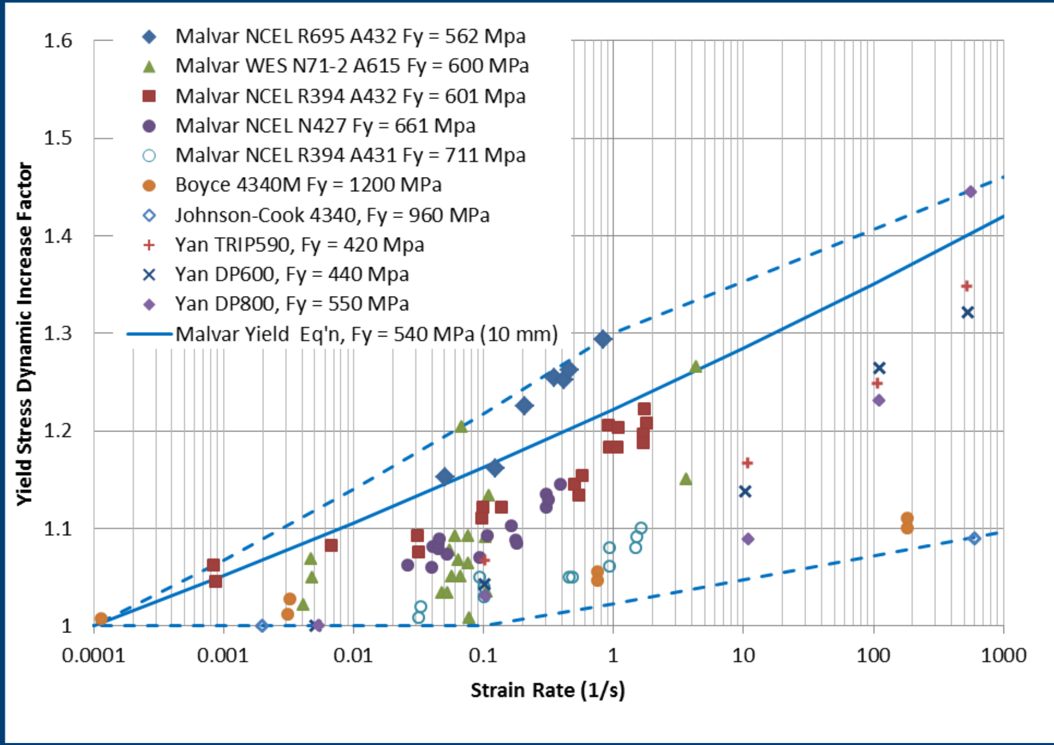
Material Model Calibration: Strain Rate Effects

- Lots of variability

Concrete



Steel



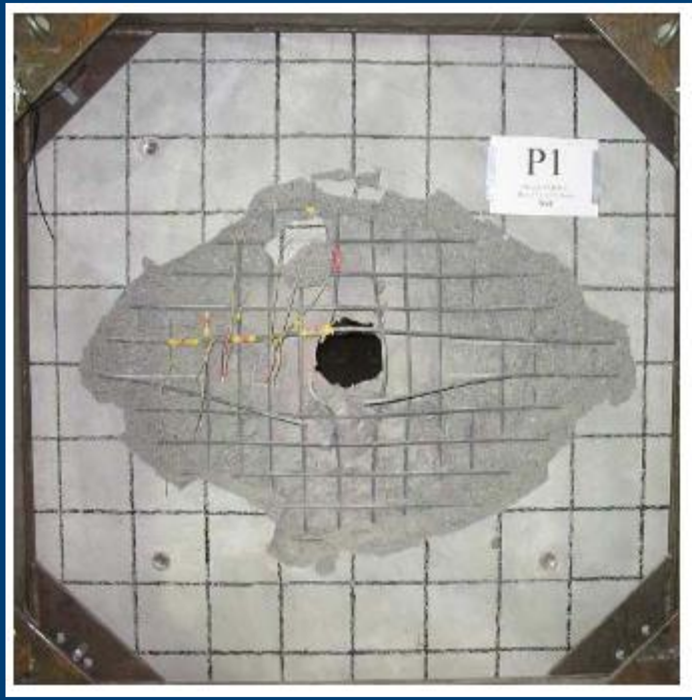
Benchmark Against Appropriate Experiments

- Validate methodology for a carefully planned and executed test involving similar behavior to our application

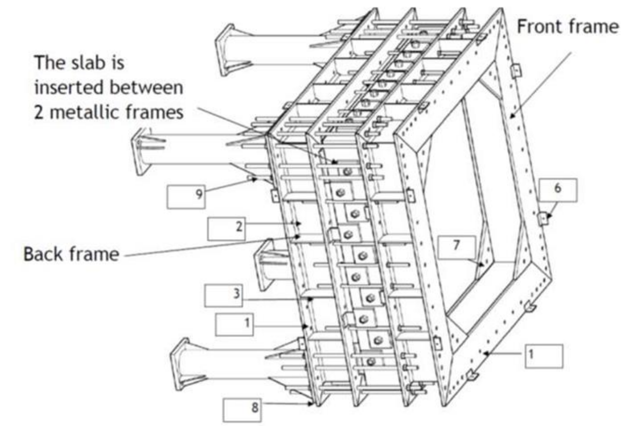
  2010-2012 IRIS experiments

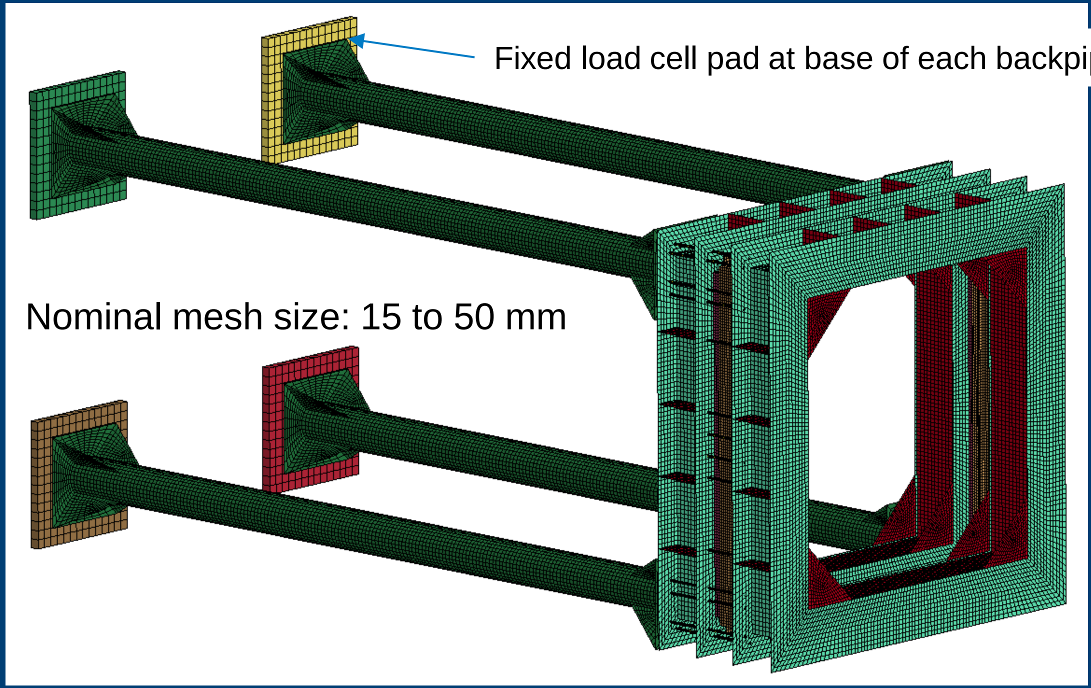
- Reinforced concrete panel impact tests
- Well-characterized material response
- Appropriate loading: flexure and puncture tests

IRIS Experiments



Test Frame





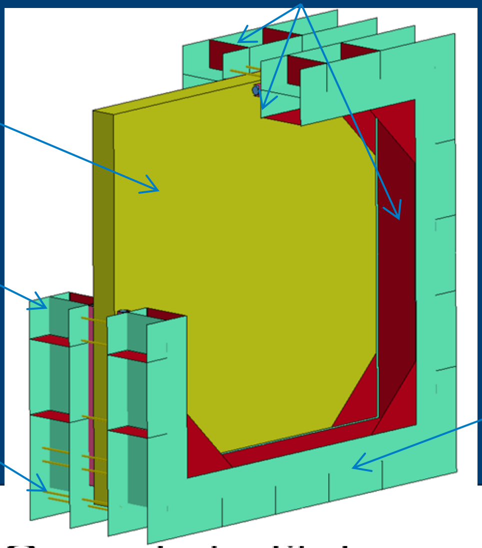
Fixed load cell pad at base of each backpipe

Reinforcing gussets and plates (shells)

Test Panel (bend test panel shown)

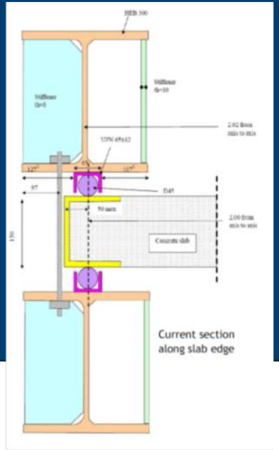
Rear frame (shells)

Frame sandwiching bolts (beams)

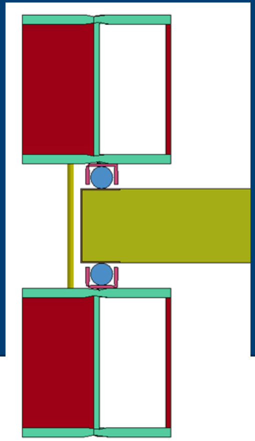


Front frame (shells)

Design Schematic



Model



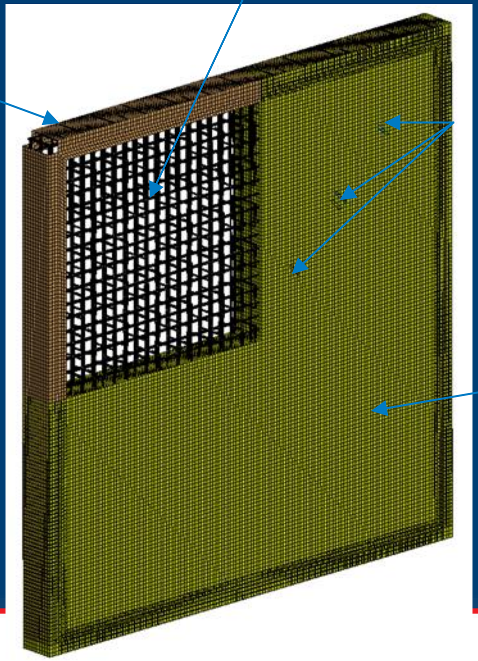
(visualized shell thickness)

Test Reinforced Concrete Panel

- Concrete: solid elements
- Rebar: beam elements
- Angle: shell elements

Embedded rebar

Corner angles

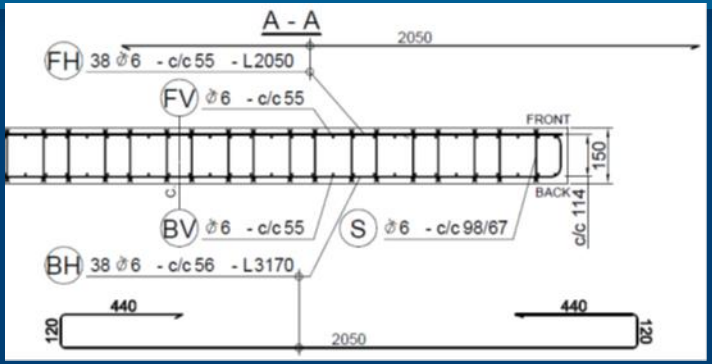


Strain gauges on panel face

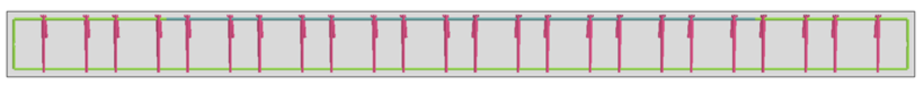
Panel concrete

Horiz. Rebar

Design

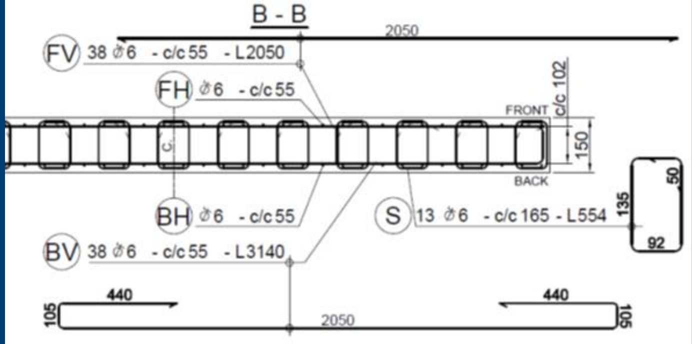


Model



Vert. Rebar

Design



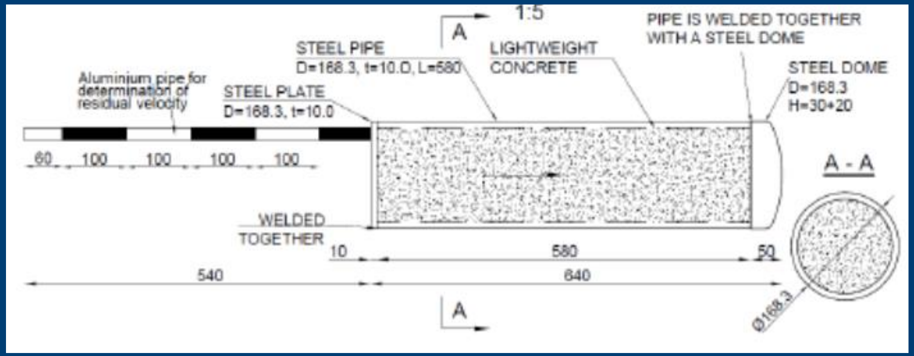
Model

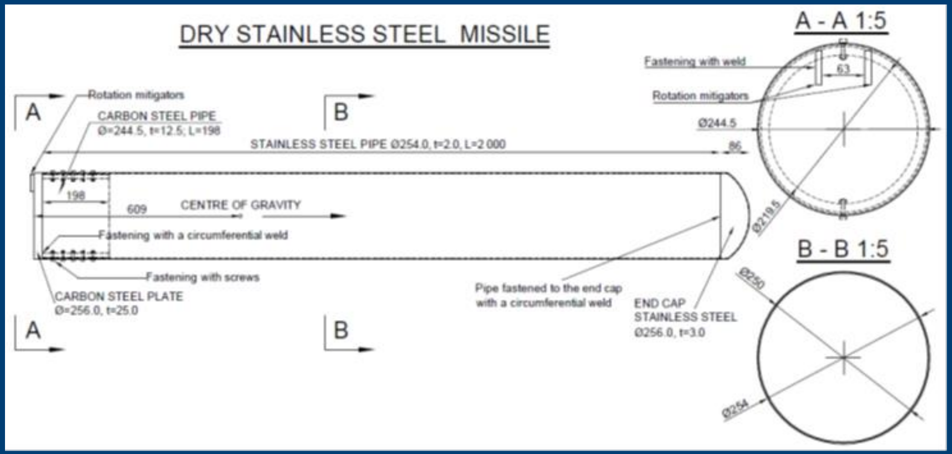
Impact Missiles

Puncture Tests

Flexure Tests

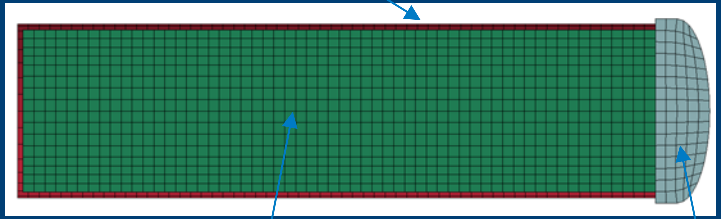
Design





Models

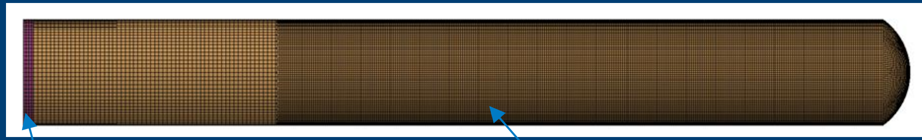
Steel Case, Shell elements



Lightweight Concrete (LWC) core, Solid elements

Steel Nose, Solid elements

Nominal element size: 5 mm in buckle zone, 10 mm aft



Thick Aft Steel Ballast, Solid Elements

Thin Hollow Stainless Steel Nose and Case, Shell Elements

IRIS Experiment Benchmarking

- Directly compare models to test observations:

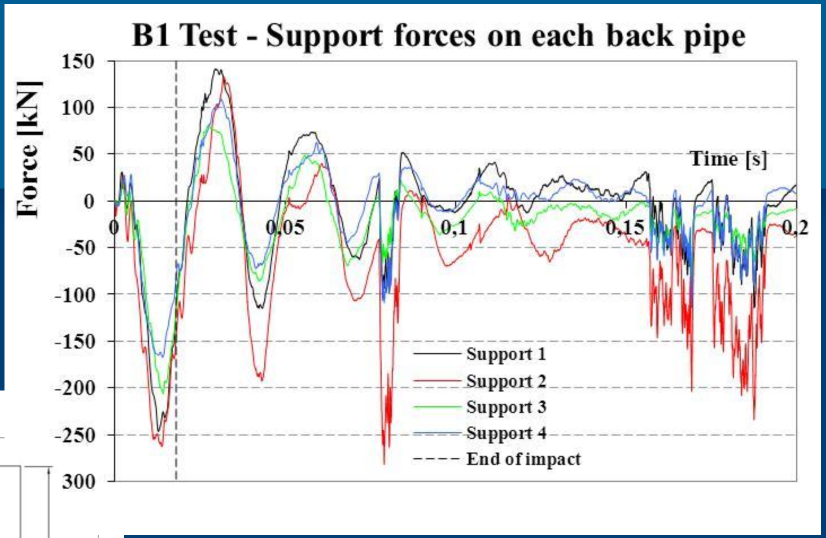
Visual/qualitative:

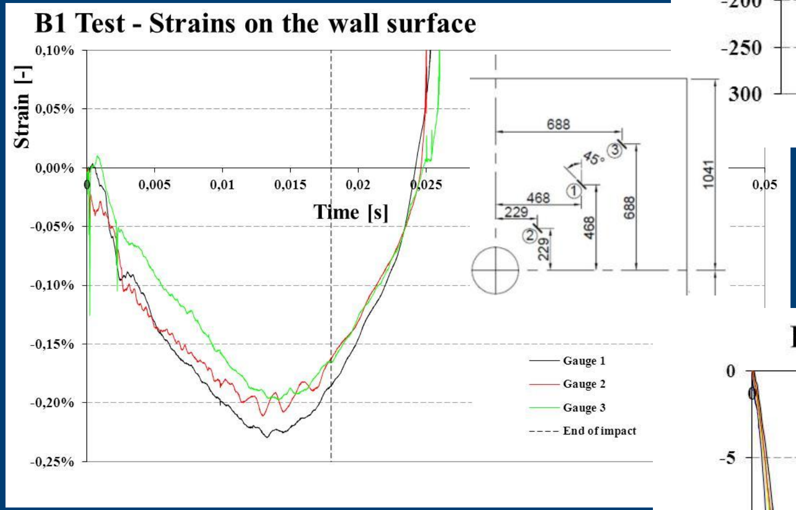
- damage, crack patterns

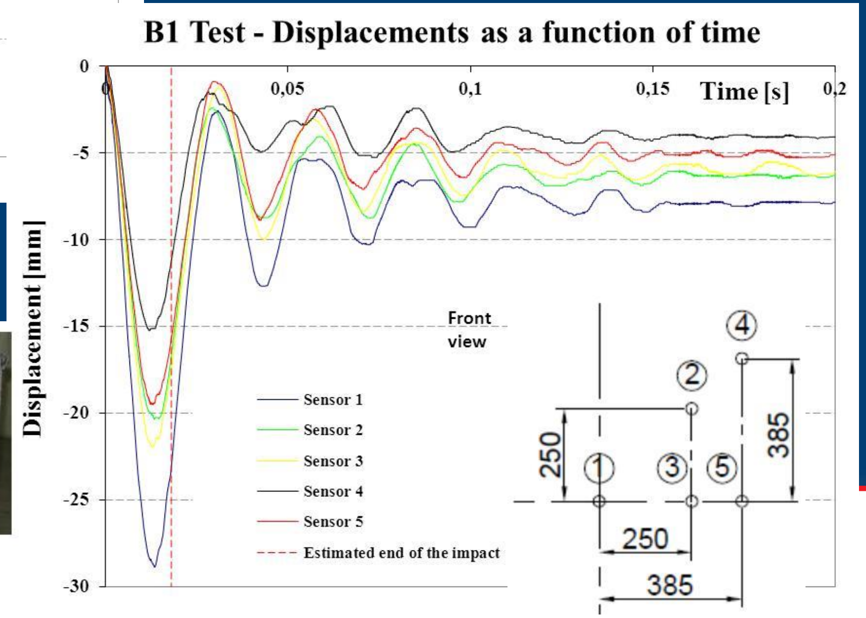
Measured/quantitative:

- Strains: concrete, rebar, frame
- Load: support
- Displacements: panel, frame

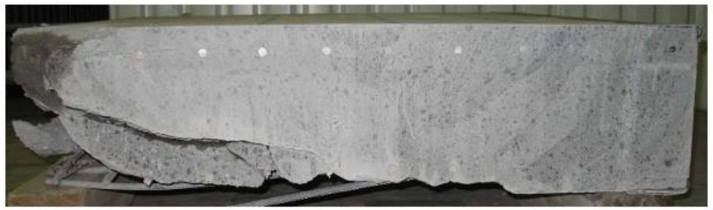
Data from VTT Bending Tests







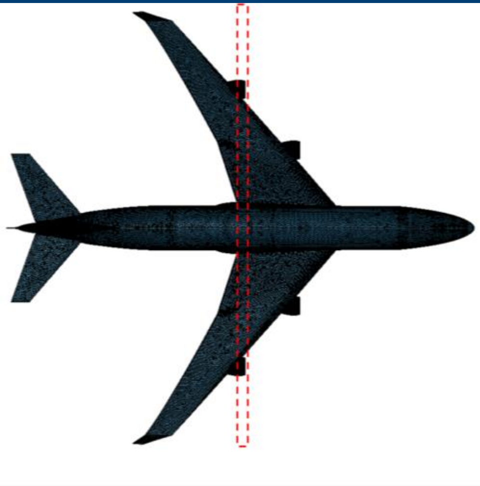
Section from Puncture Test

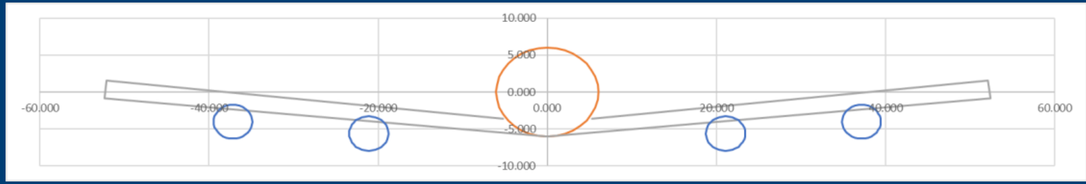


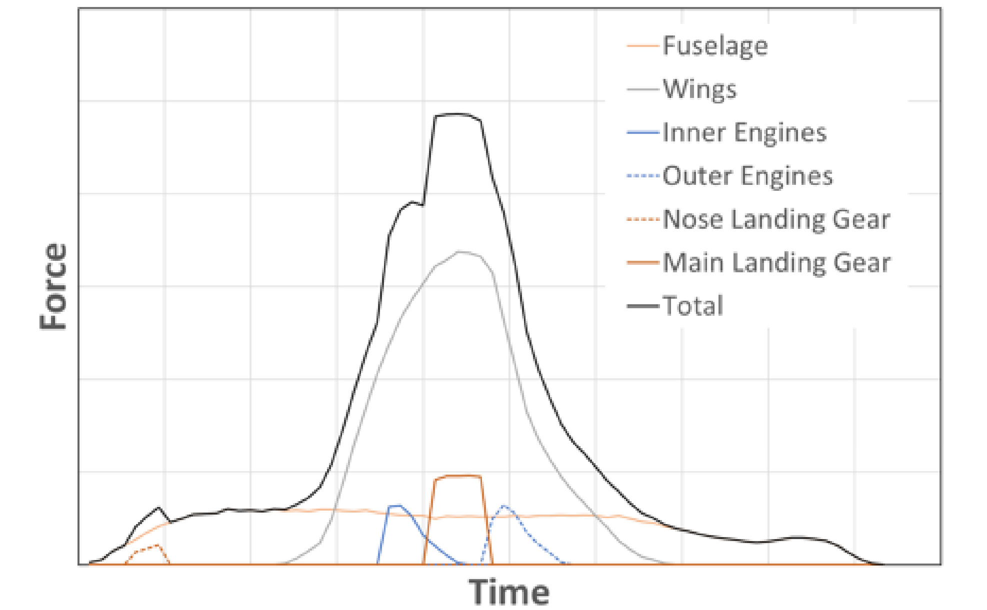
Global Modeling

- Scale up to application of interest
  - Apply established methodology + industry-accepted practice for the application (e.g., NEI 07-13)
- Checks at large scale:
  - Compare to hand calculations—is the response within expected bounds?
  - Check calculation energies, timestepping, and other usual model checks for nonlinear explicit FEA
  - Check reactions match inputs
  - Apply intuition: does the response look reasonable

Aircraft Load Development

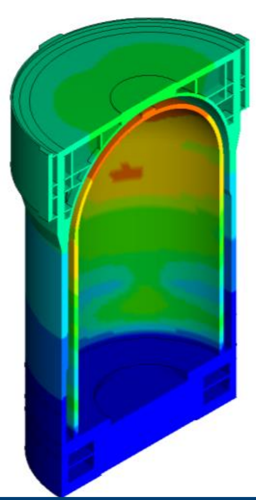


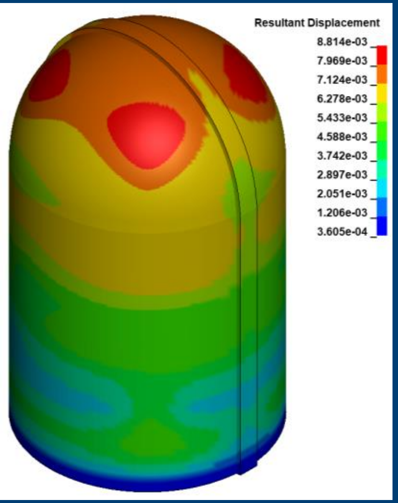




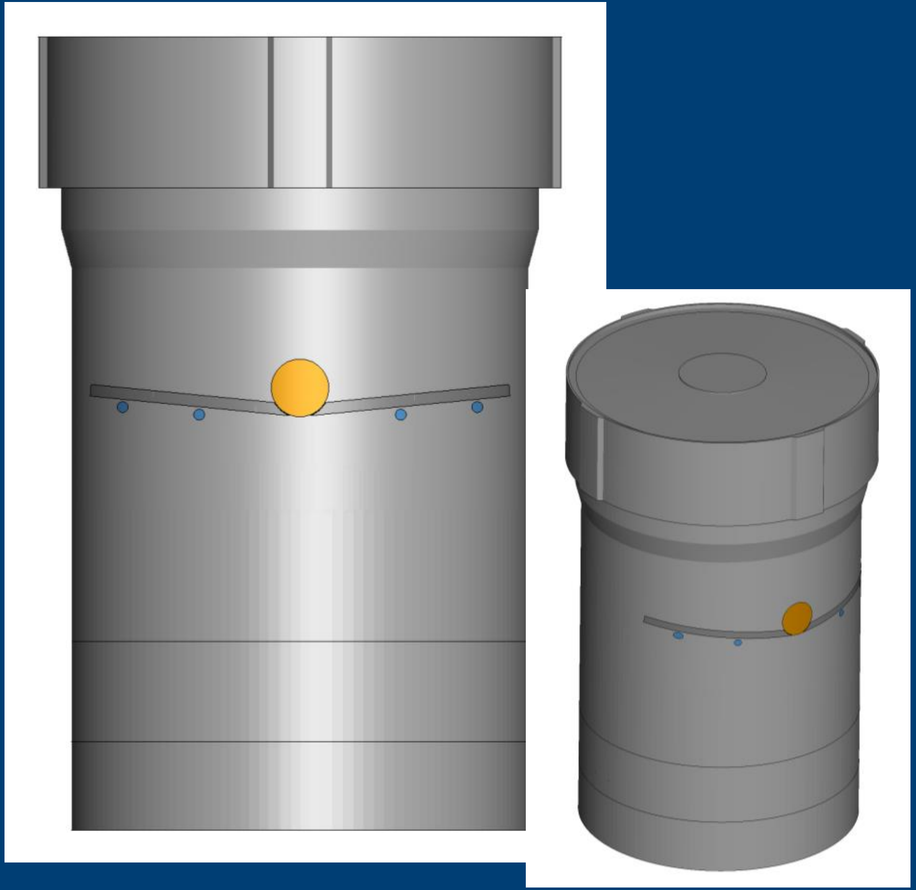
Aircraft Impact Analysis

Initialized Model

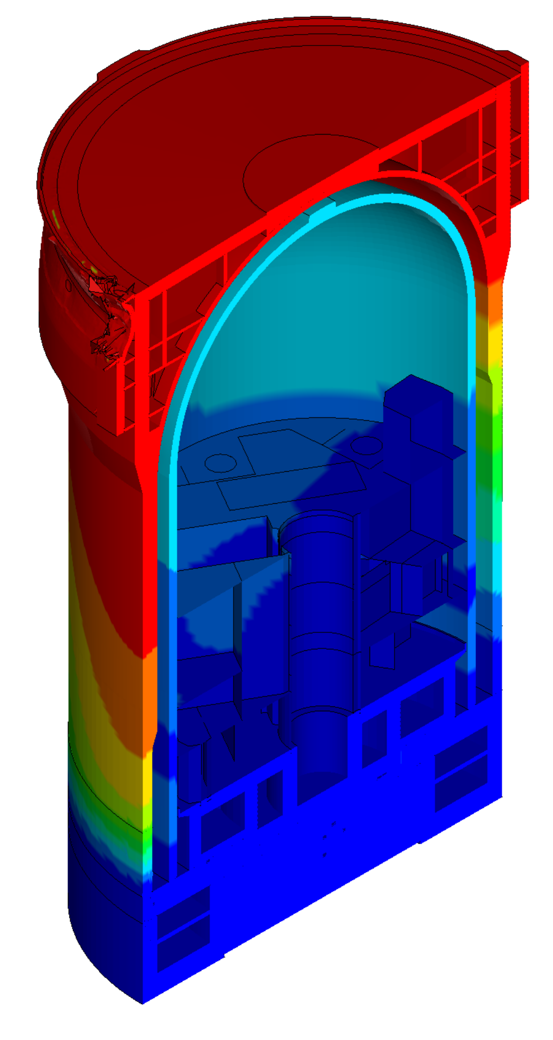




Load Application Example



Post Impact Response



Summary

- Valid modeling approaches start with planning and proper selection of model approach
- Validation and Verification should be performed at all stages of methodology development
- Start simple and build up complexity, validating/verifying against known responses along the way
  - Characterize fundamental material response
  - Compare to testing and other verification means

Questions for Audience

- What V&V steps do you employ in your nonlinear analyses?

Thank you

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www.concrete.org