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Team 13—Sandia National Labs and US NRC

VeRCoRs Mechanical Response to Environmental Effects

Presenter: Dr. Josh Hogancamp, SNL

VeRCoRs Benchmark III

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Saclay, France

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Introduction: Team 13

Team members:

- Josh Hogancamp—Primary analyst, Sandia National Labs
- John Wilkes—Principal investigator, Sandia National Labs
- Madhumita Sircar—Project manager, US Nuclear Regulatory Commission
- Christopher Jones—Project consultant, Kansas State University

Primary analysis considerations:

- Mechanical response (stresses, strains, and deformations) to stimuli including posttensioning and drying
- Did not analyze for cracking

Outline

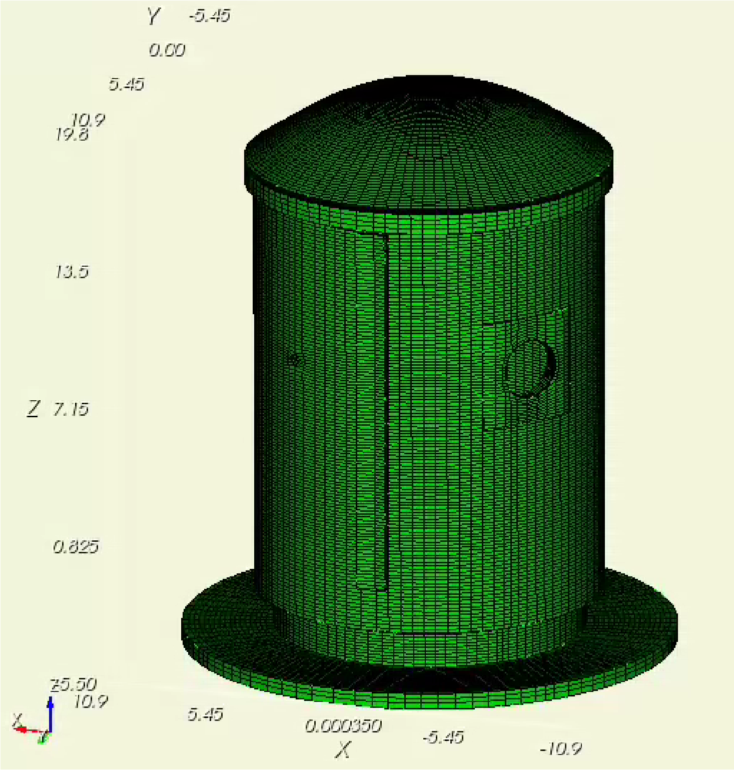
- Geometry & Mesh
- Boundary Conditions, Initial Conditions, and Stimuli
- Materials: Tendons, Rebar, Concrete
- Results: Mechanical stresses & strains
- Results: Effect of creep and humidity
- Results: Mesh convergence

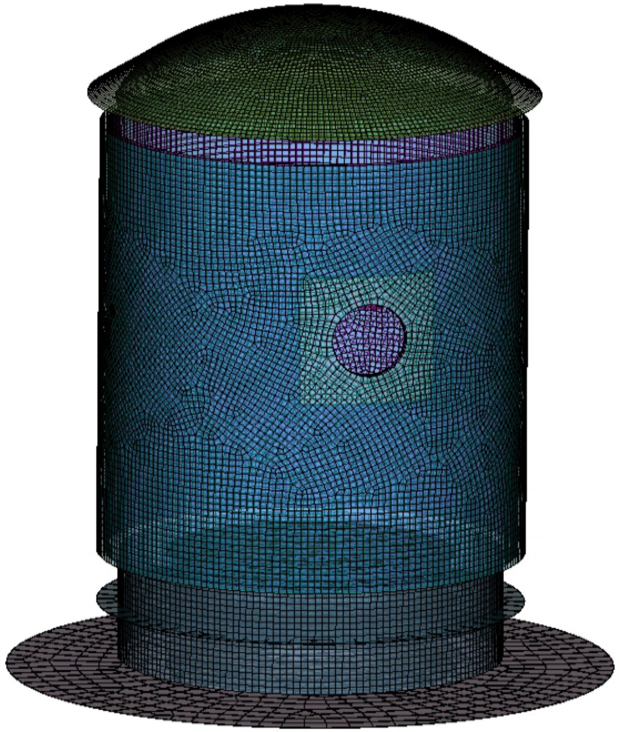
Geometry: Overview

- Containment vessel concrete and posttensioning tendon geometries were provided by EDF
- Concrete and tendon meshes were created utilizing Cubit
- Rebar geometry and mesh were created utilizing Cubit
- Rebar size and spacing were determined from drawings provided by EDF
- Rebar layers were added to the simulation as surface elements
- Surface elements in ABAQUS have orthotropic properties depending on reinforcement ratios in each direction

Geometry

- Explicitly modeled: posttensioning tendons, rebar (using ABAQUS surface elements), and concrete



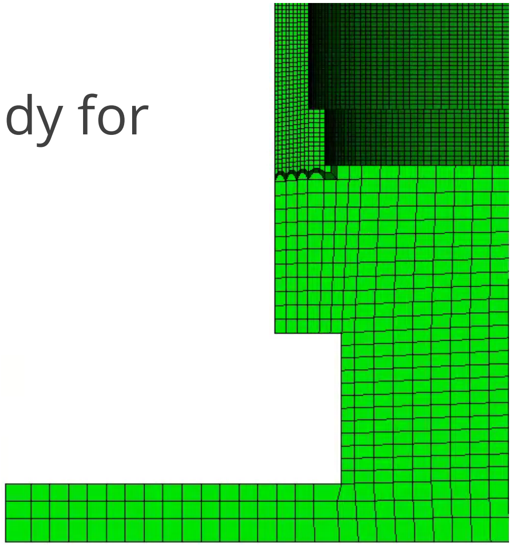
Geometry: Concrete

- Concrete represented with 8-node hexahedral elements

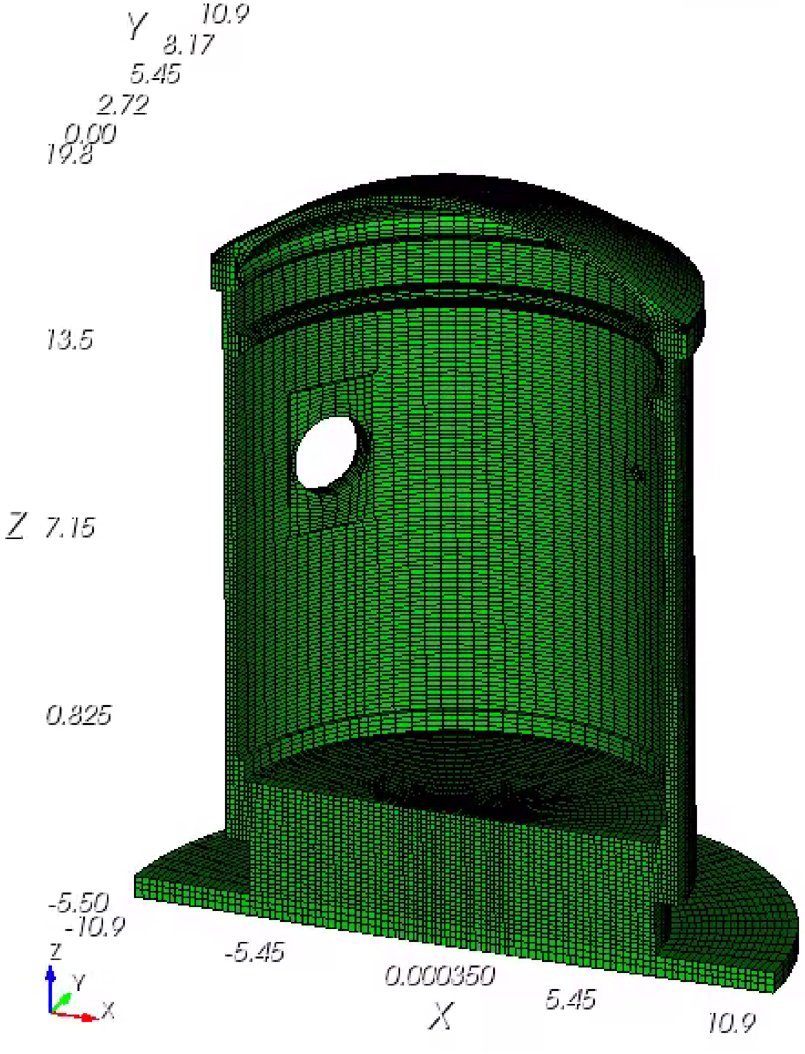
- Mesh convergence study – elements thru wall & dome

Resolution	Wall & Dome X-SXN	Element count	Element Size
Course	5 & 3	138,384	~0.15 m
Semi-fine	8 & 5	406,707	~0.09 m
Fine	11 & 9	1,463,472	~0.04 m

- Pedestal not modified for study for computational efficiency



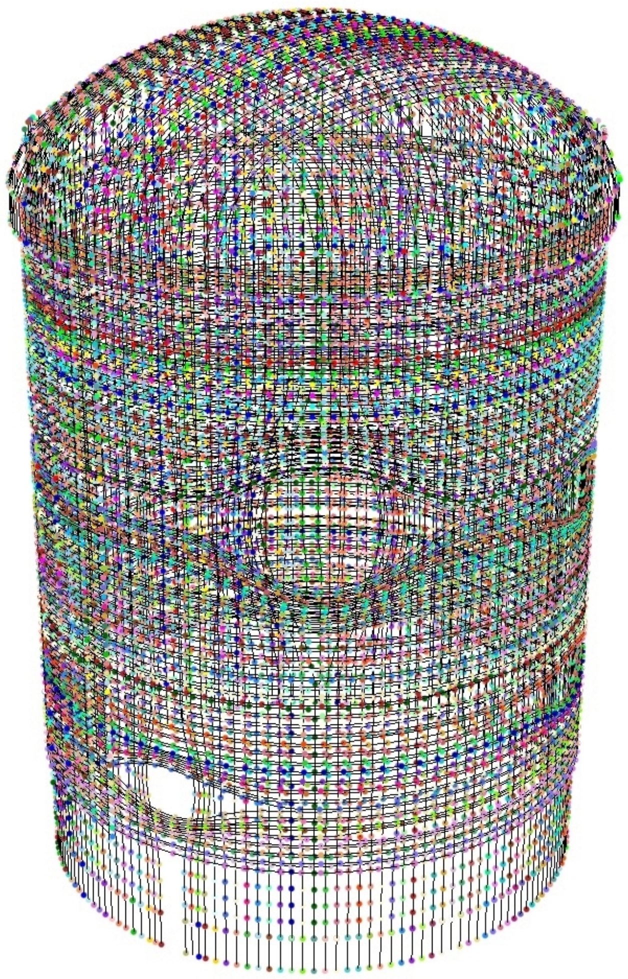
Fine mesh



Coarse mesh

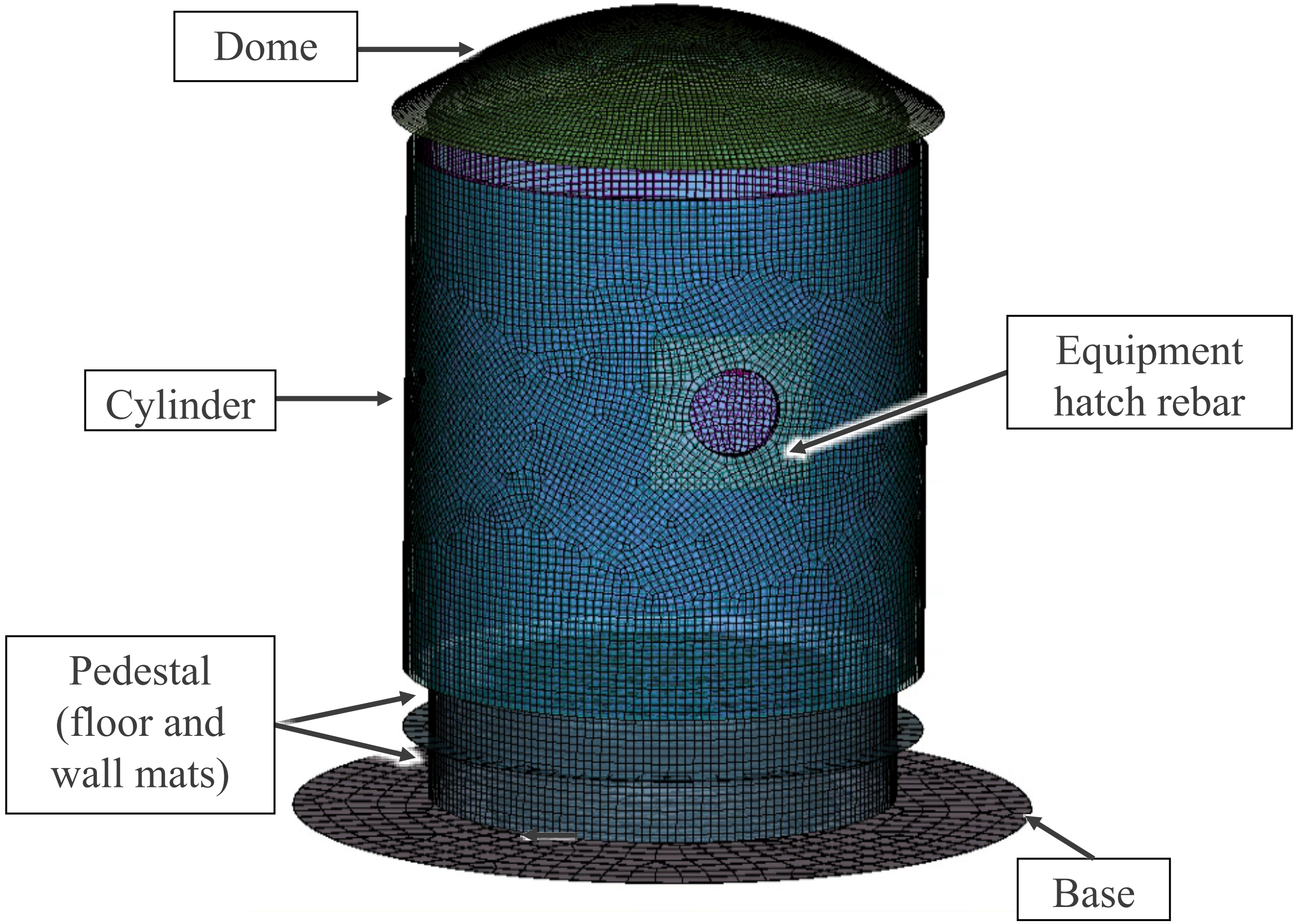
Geometry: Tendons

- 44,466 2-noded beam elements
- Each element ~ 0.5 m long
- Vertical, hoop, and dome tendons all explicitly modeled
- Tendon elements were embedded into the concrete elements allowing for zero slip



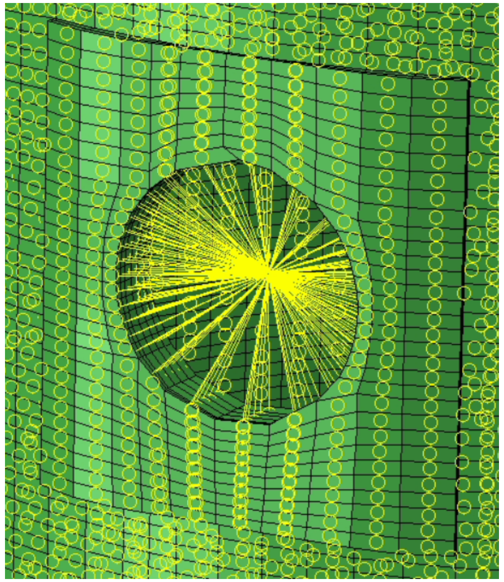
Geometry: Rebar

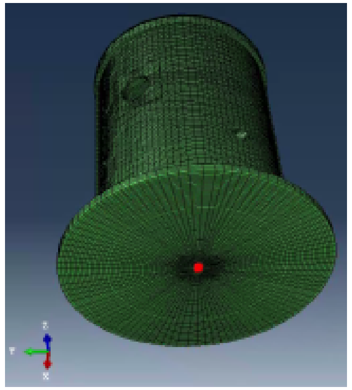
- 35,172 4-noded surface elements
- 2x rebar layers added at all penetrations to account for additional reinforcement
- Utilized ABAQUS rebar surface-layer function
  - ABAQUS-specific element type designed for rebar layers
  - Orthotropic properties along the surface elements
  - No properties out of plane to the surface elements

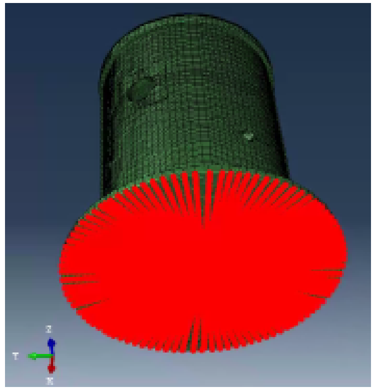


Boundary Conditions: Concrete

- All nodes on bottom of CV fixed against gravity with 6 central nodes fixed against all movement (to prevent numerical structural rotation)
- Pressurizations applied uniformly to all nodes on the inner surface of the CV
- Each penetration had an equivalent force node at its center to account for pressure applied to penetration covers (i.e. the pressure applied to the equipment hatch)

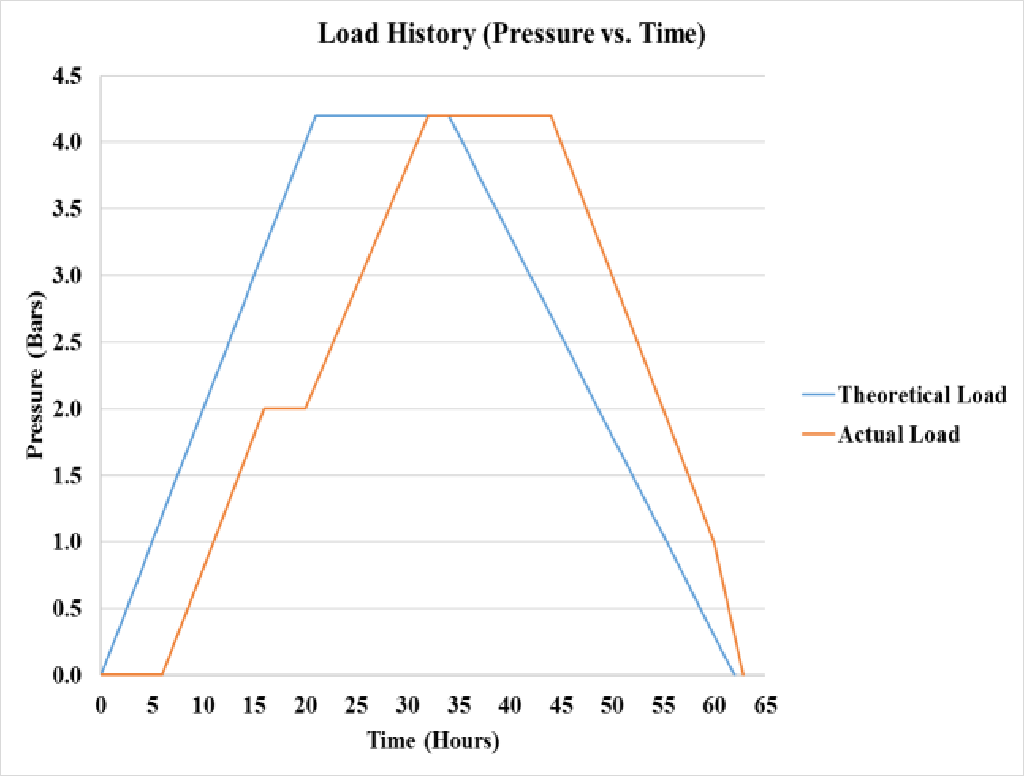






Boundary Conditions: Internal Pressurization

- Internal pressurizations were based on the “actual” load from a previous benchmark test. The difference between load profiles is negligible.



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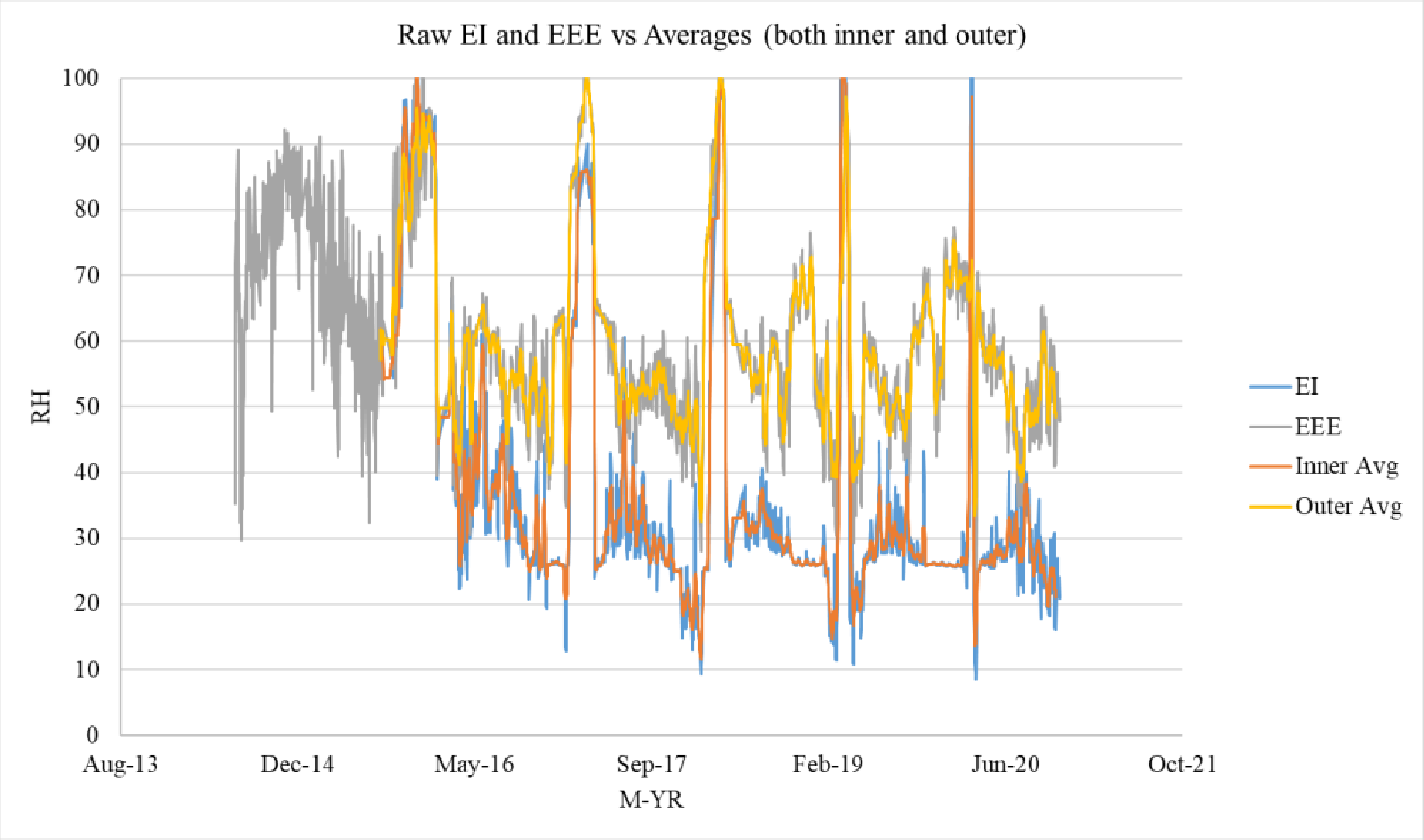
Boundary Conditions: Relative Humidity

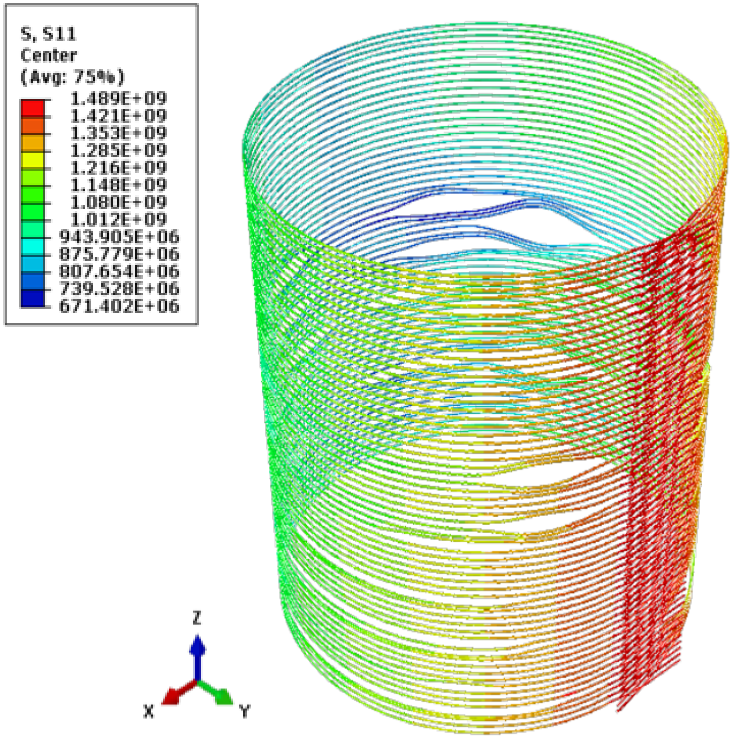
- Relative humidity was essential for matching simulation results to past experimental data
- Utilized a moving average to reduce noise
- Inner and outer RH profiles applied to their respective surfaces



Initial Conditions and Tendon Tensioning

- Gravity was included in the simulation, but no thermal effects due to variation of ambient/environment temperature
- RH in the concrete was assumed at an initial 60%, and changes were applied based on the previous slide
- Each tendon was tensioned by “pulling” the tendon at the location where the tendon extrudes from the concrete (mimicking the actual tensioning method)
- The tendon pulling algorithm restricted the tendons to their own geometry and included friction effects

Example tendon stresses



Material Properties: Steel

- Rebar:
  - Linear elastic—assumed that no rebar would yield in the simulation
  - Young's modulus = 200 GPa, fy = 500 MPa, $\nu = 0.30$, $\rho = 7850$ kg/m^3
- Tendons:
  - Linear elastic—assumed that no tendons would yield in the simulation
  - Young's modulus = 190 GPa, fy = 1620 MPa, $\nu = 0.30$, $\rho = 7850$ kg/m^3
- No steel is expected to yield

Material Properties: Concrete

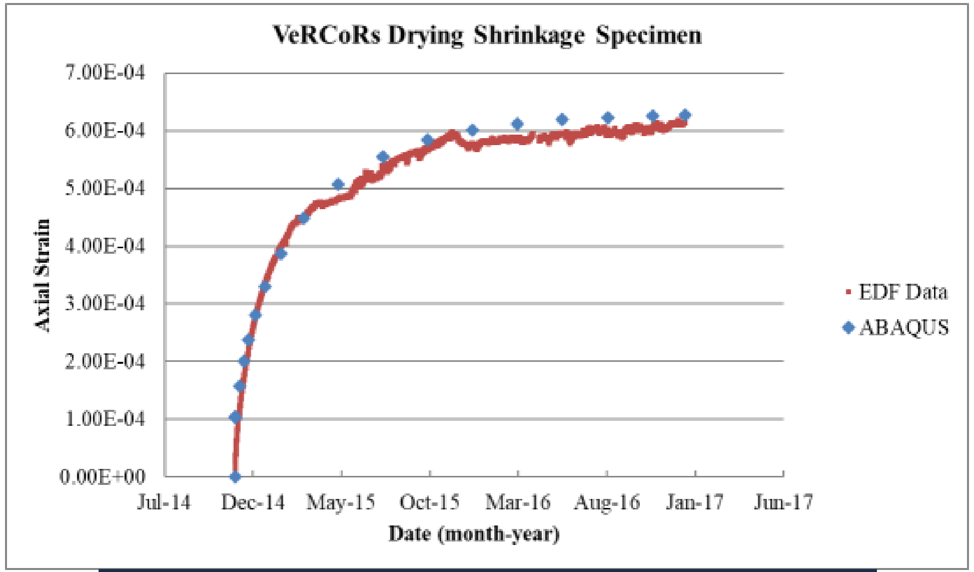
- Concrete was modeled to include elastic, creep, and drying shrinkage effects
- Elastic: Young's modulus = 34.3 GPa, f'c = 50 MPa, ν = 0.20, $\rho = 2390$ kg/m^3
- Drying shrinkage: modeled using Fick's 2nd Law of Diffusion (more in later slide)
- Creep: modeled using Bazant's B3 creep model (more in later slide)
- Not included: thermal effects due to variation of ambient/environmental temperatures

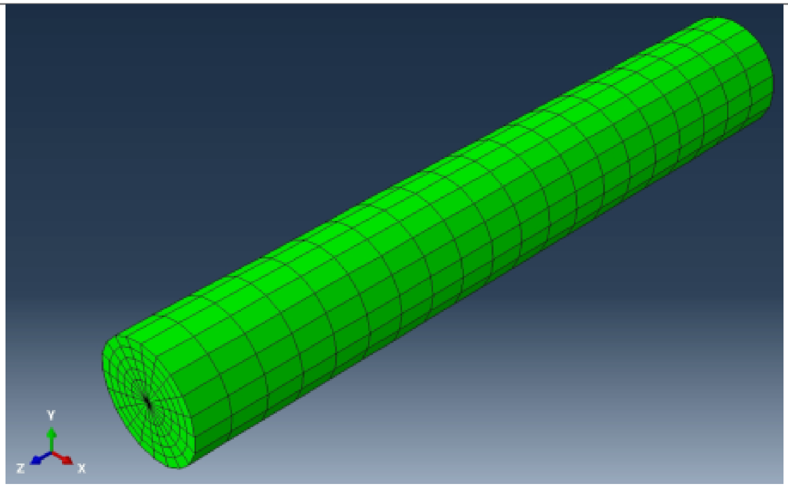
Material Properties: Concrete Drying Shrinkage

- Fick's 2nd Law: $\frac{\partial C}{\partial t} = \gamma \nabla^2 C$
- ABAQUS thermal equation: $\frac{\partial u}{\partial t} = \frac{k}{c_p \rho} \nabla^2 u$
- Use the ABAQUS thermal equation to implement drying shrinkage based on relative humidity:
  - u is the RH as a function of space and time;
  - ∂u/∂t is the rate of change of RH at a point over time;
  - $\nabla^2 u$ are the second spatial derivatives of RH in the x, y, and z directions;
  - k is the RH 'conductivity';
  - c_p is the 'specific RH capacity';
  - ρ is the mass density;
  - α is the 'coefficient of drying shrinkage expansion'.
- Using the thermal equation for drying shrinkage meant that we could not also use the thermal equation for thermal effects

Material Properties: Concrete Drying Shrinkage

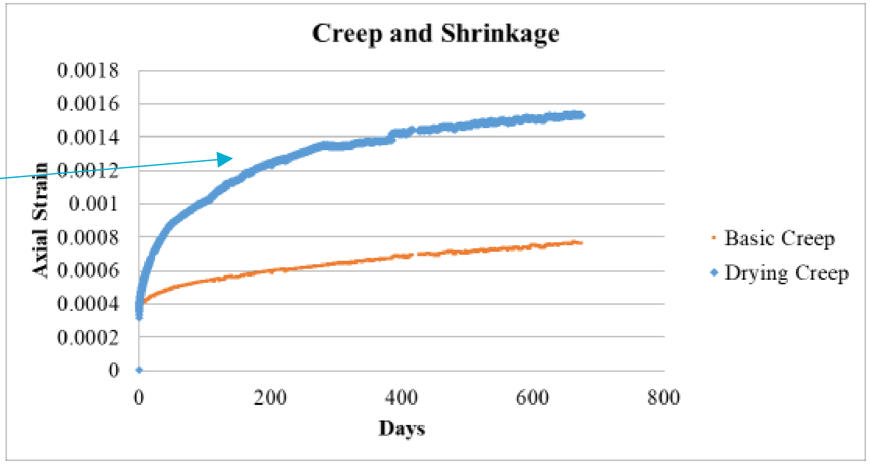
- A cylinder of concrete was cast, cured for 28 days, and then exposed to a dry environment of 50% RH for 762 days by EDF for the VeRCoRs experiment
  - Density: 2390 kg/m^3
  - Young's modulus: 34.26 GPa
  - Poisson's ratio: 0.20
  - RH 'Expansion coefficient': 0.0014 m^3/ΔRH
  - RH 'Conductivity' (from literature): 1.0 x 10^{-10} RH/(m·s·ΔRH)
  - Specific RH capacity': 0.0004 RH/(kg·ΔRH)

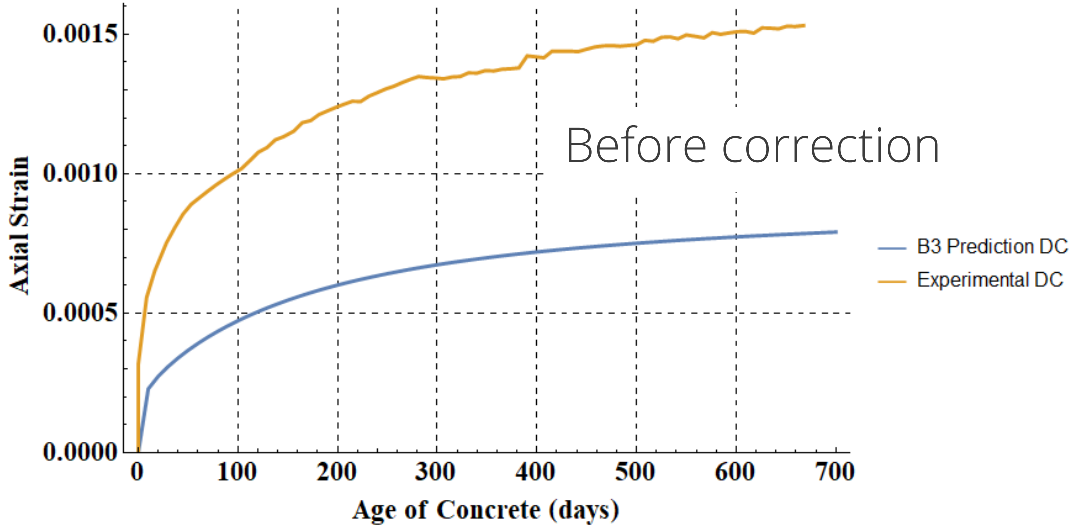


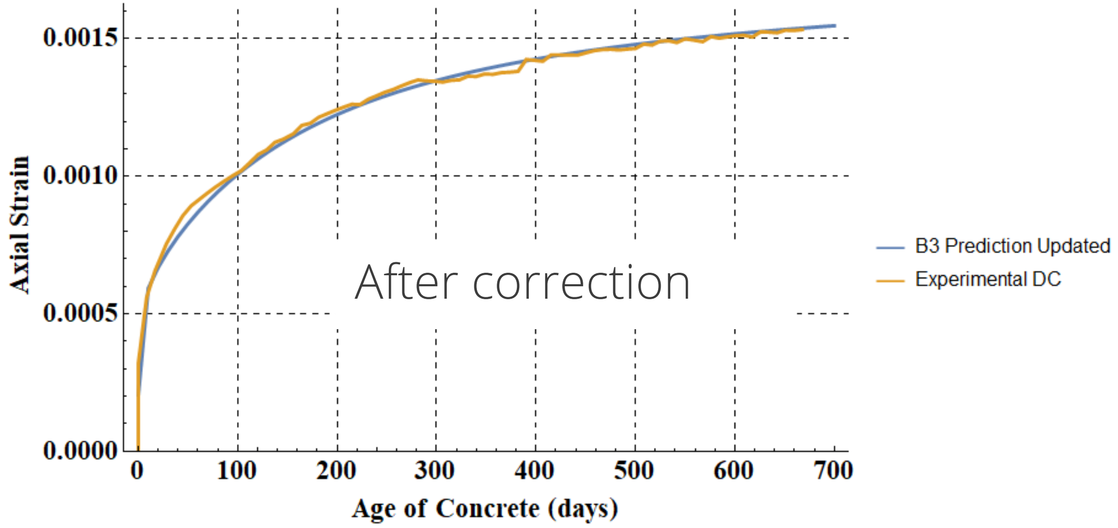


Material Properties: Concrete Creep

- Both surfaces of the concrete were exposed to low RH, so used EDF's drying creep data
- Bazant B3 creep model utilizes experimental data to correct for model inaccuracies (modeling concrete creep without experimental data is extremely difficult)







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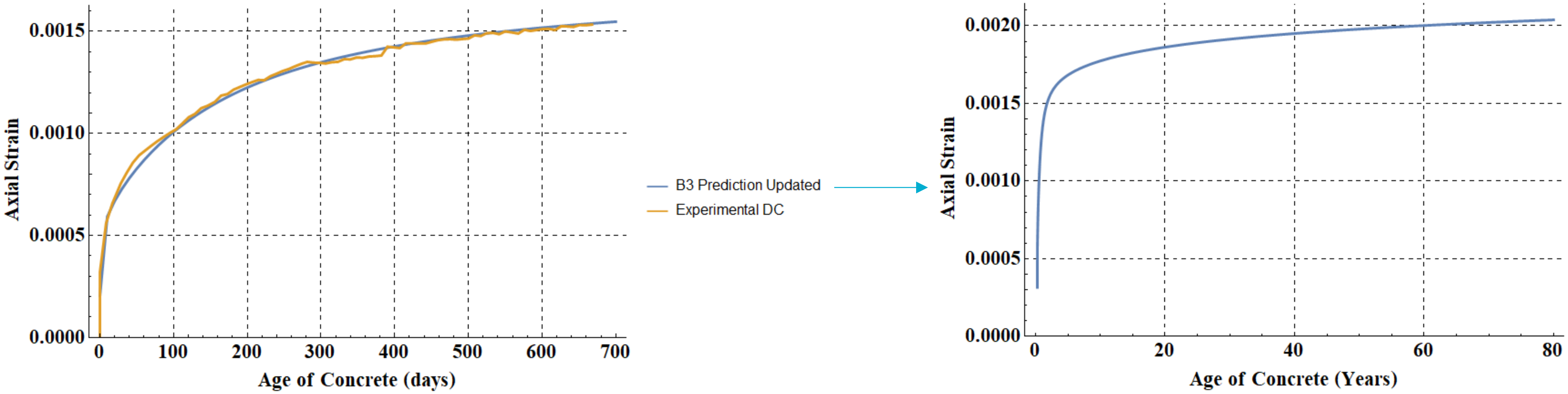
Material Properties: Concrete Creep

- Use Bazant B3 model with experimental data to predict creep to 80 years
- Implement into ABAQUS using ABAQUS creep model via a prony series (series of exponential terms to match 80 year curve)



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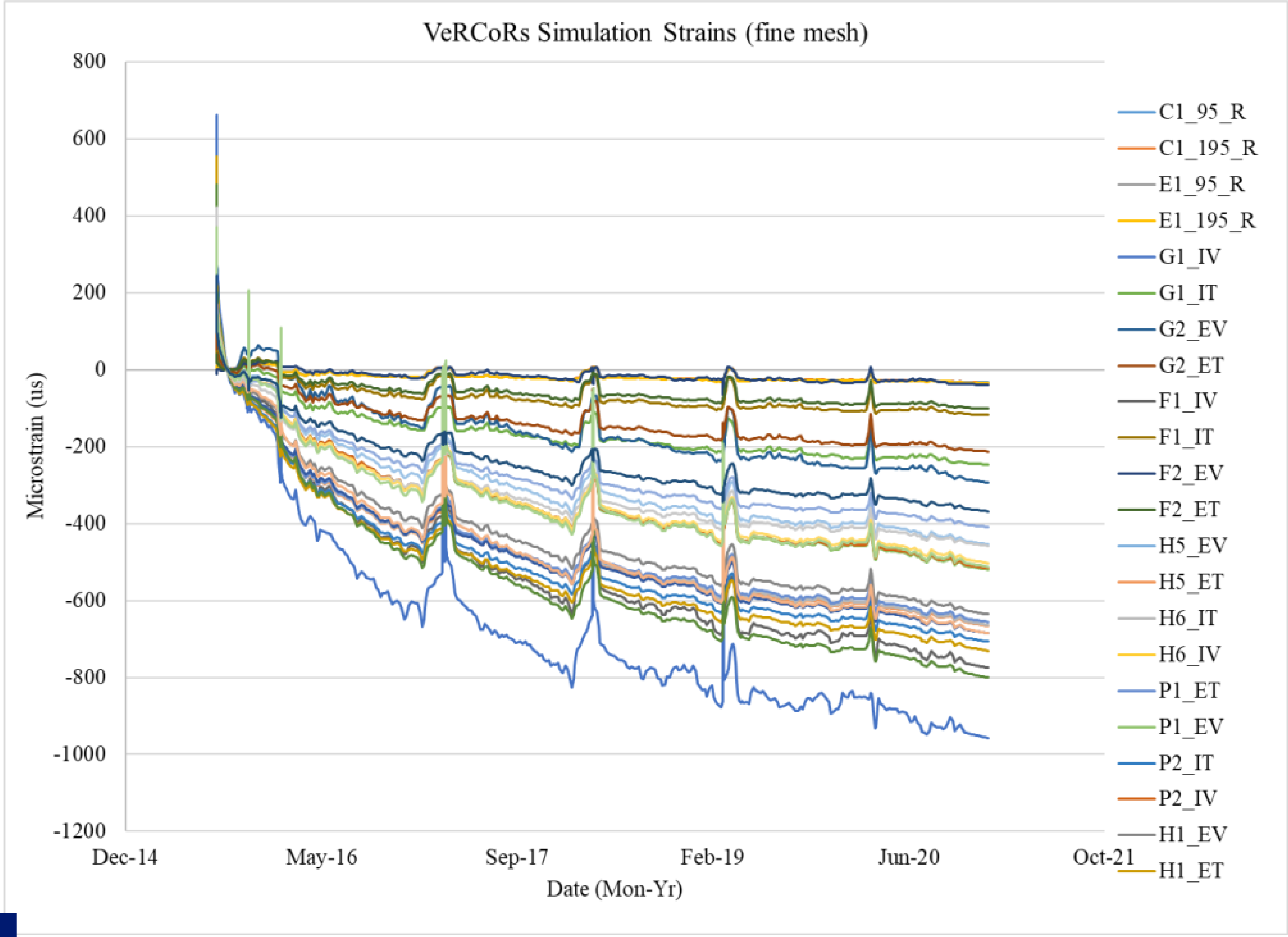
Simulation Timeline (dates in Month/Day/Year format)

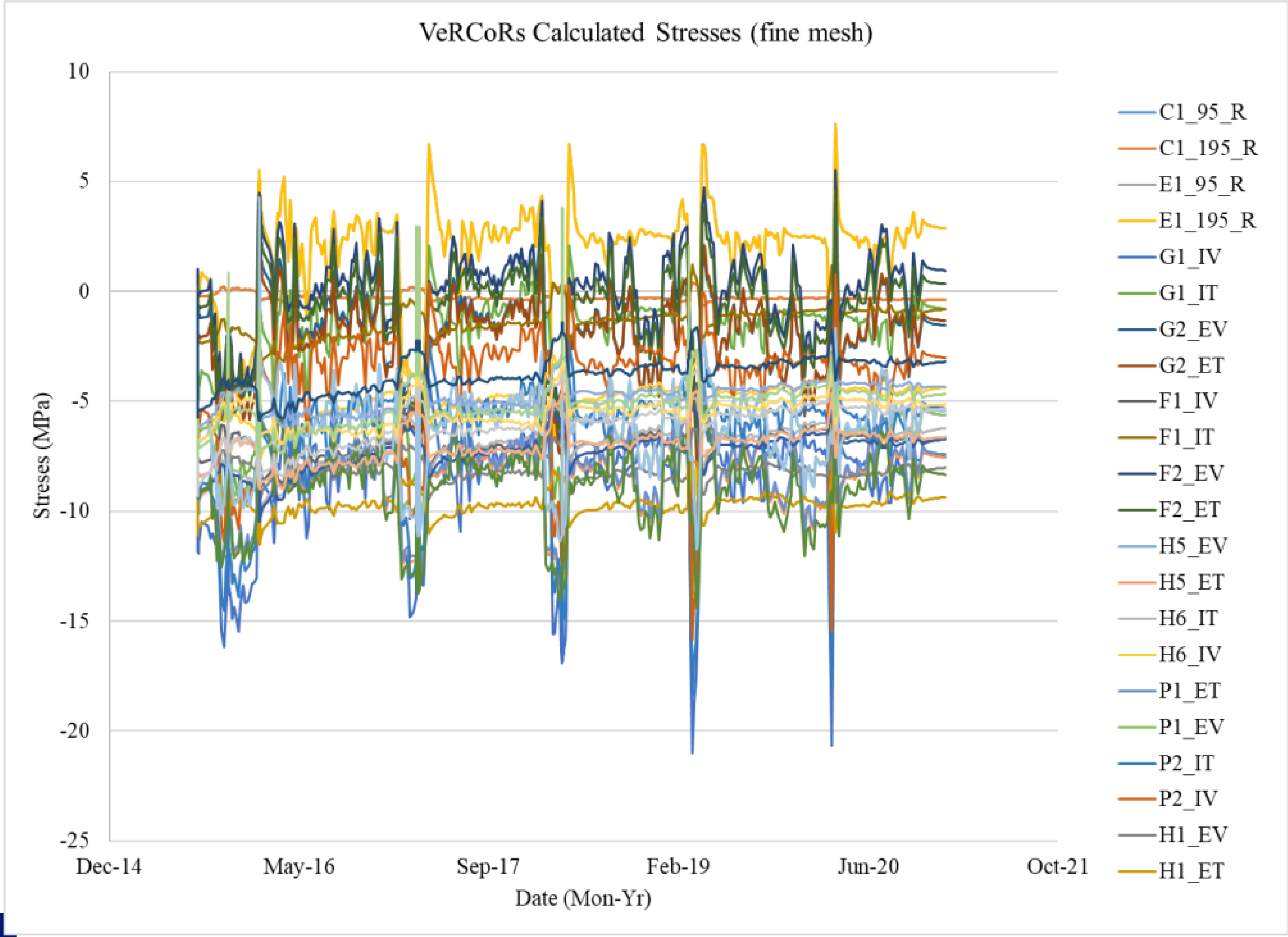
Step Title	Date Begin	Date End	Total Time (days)	Description
Initialize	N/A	N/A	10 seconds	Ramp gravity and post-tensioning loads
0	8/17/2015	11/2/2015	77.0	Post-tensioning complete, await first pressurization
1	11/2/2015	11/4/2015	2.2	Strains reference date 11/2/2015
2	11/4/2015	11/6/2015	2.4	Pressurization ‘Pre-op’
3	11/6/2015	1/25/2016	80.0	Dormant period
4	1/25/2016	1/28/2016	2.4	Pressurization ‘VC1’
5	1/28/2016	3/14/2017	411.2	Dormant period
6	3/14/2017	3/16/2017	2.4	Pressurization ‘VD1’
7	3/16/2017	3/21/2017	4.6	Dormant period
8	3/21/2017	3/23/2017	2.4	Pressurization ‘VD1 bis’
9	3/23/2017	4/2/2018	374.6	Dormant period
10	4/2/2018	4/4/2018	2.4	Pressurization ‘VD2’
11	4/4/2018	3/1/2019	330.1	Dormancy period
12	3/1/2019	3/3/2019	2.4	Pressurization ‘VD3’
13	3/3/2019	3/1/2021	728.6	Dormancy period
14	3/1/2021	3/3/2021	2.4	Pressurization ‘VD5’

Results: Simulation Strains (fine mesh)



Results: Simulation Stresses (fine mesh)

Negative stress
=
compression



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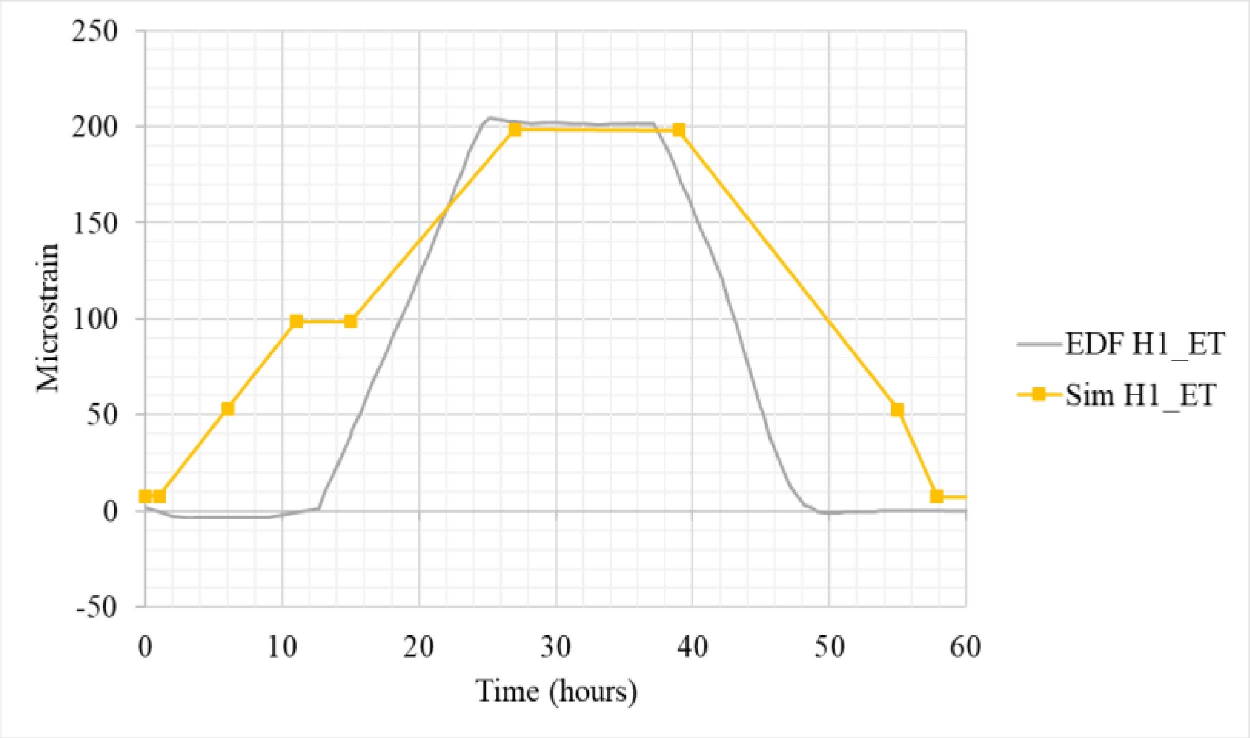
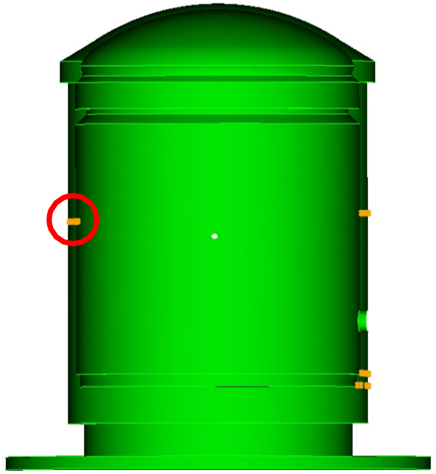
Results: Pressurization Strains Comparison

- The strains for H1ET during a pressurization event indicate that the simulation mechanical response to a pressurization was the same magnitude as the VeRCoRs Benchmark 2018 experimental data
- This indicates that the elastic mechanical response of the simulation was accurate

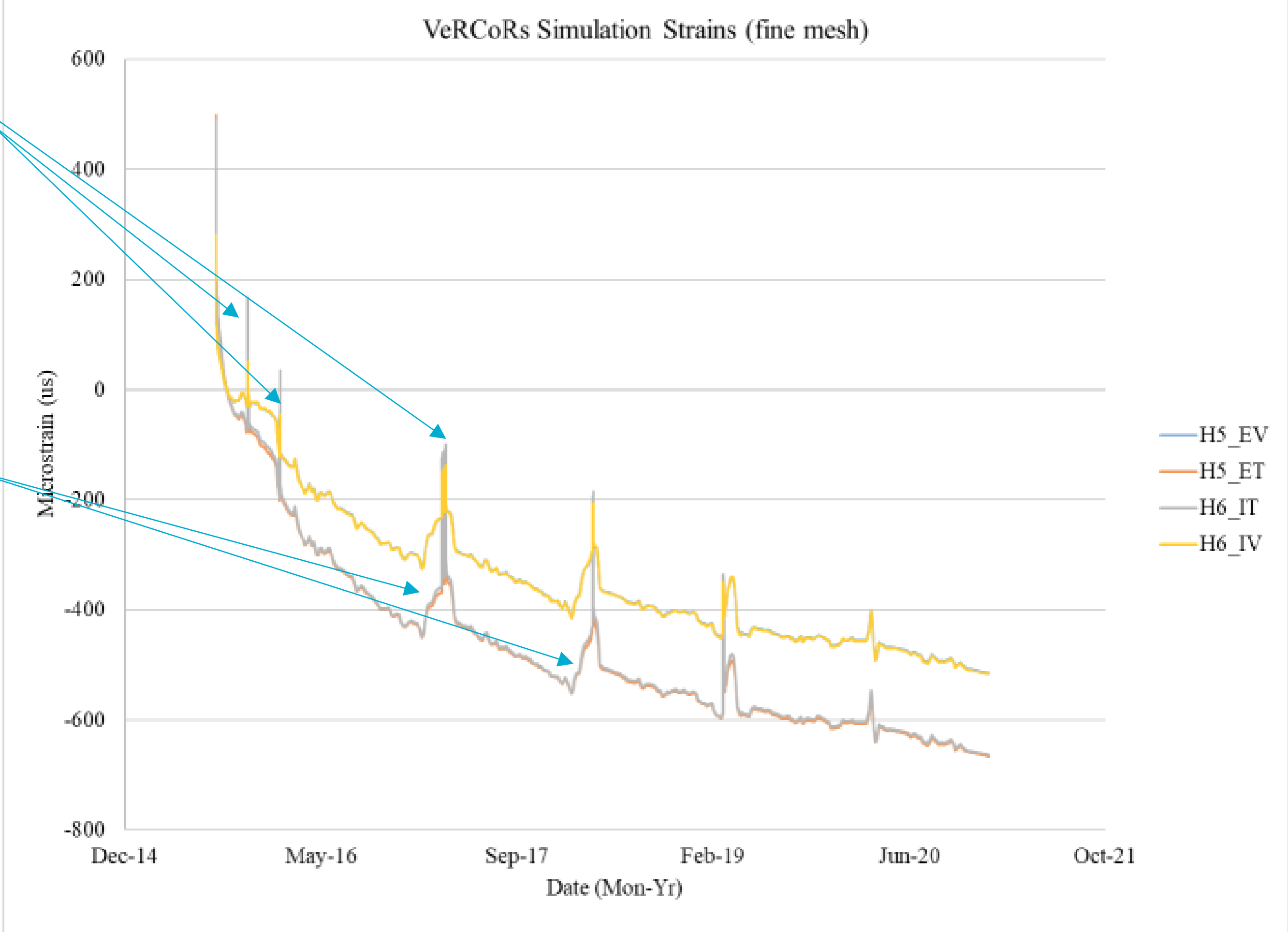


Results: Simulation Strains H5 & H6



Narrow spikes are pressurization events

The 'hills' in the data are exposure periods to higher RH



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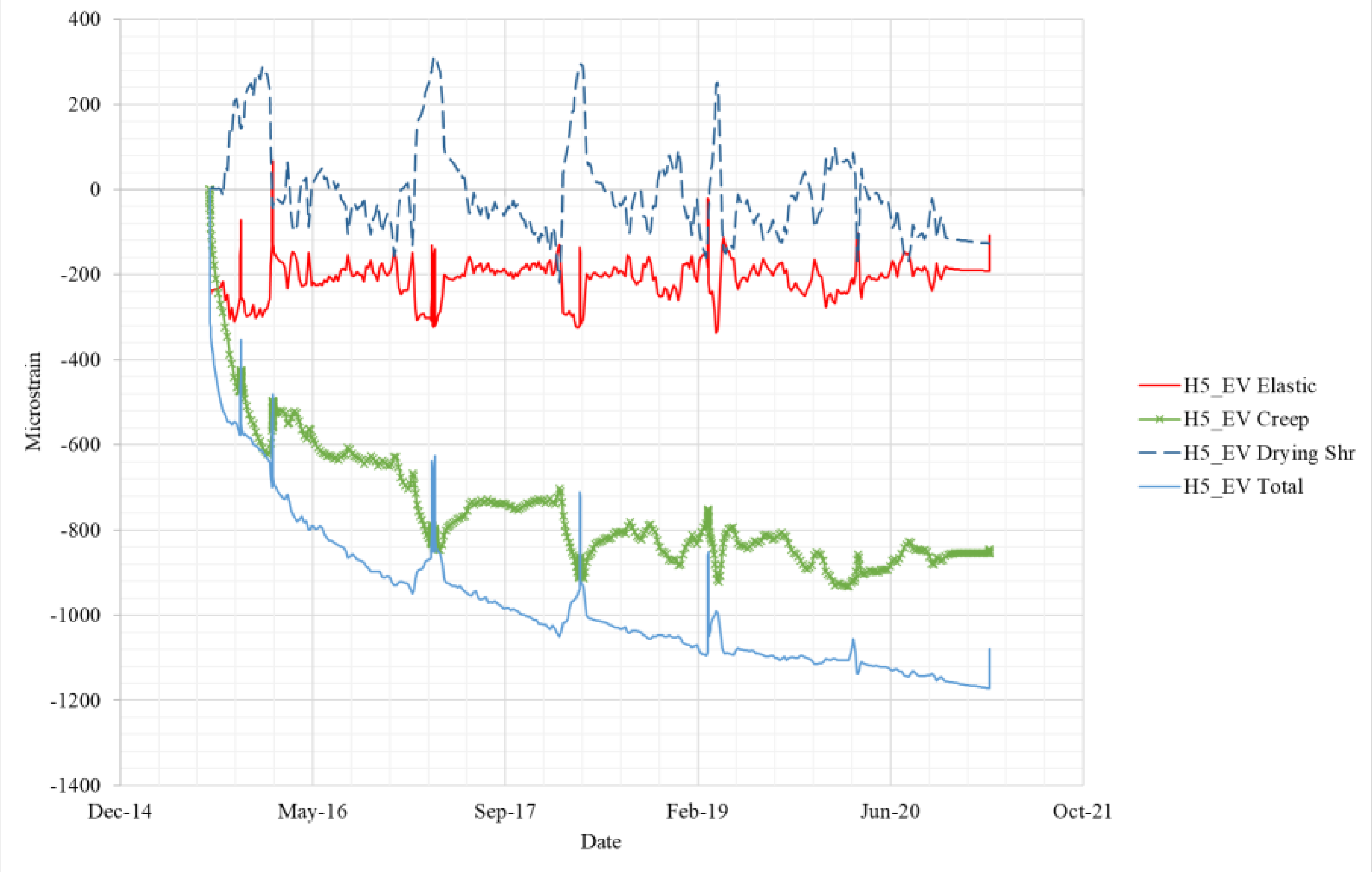
Results: Compare Simulation Types of Strains

- Example results showing linear, creep, and drying shrinkage strains
- Both drying shrinkage and creep play important roles in shaping the data
- Creep causes continuing downward trend in strain due to posttensioning tendons
- Drying shrinkage causes in “rises” in data near pressurizations



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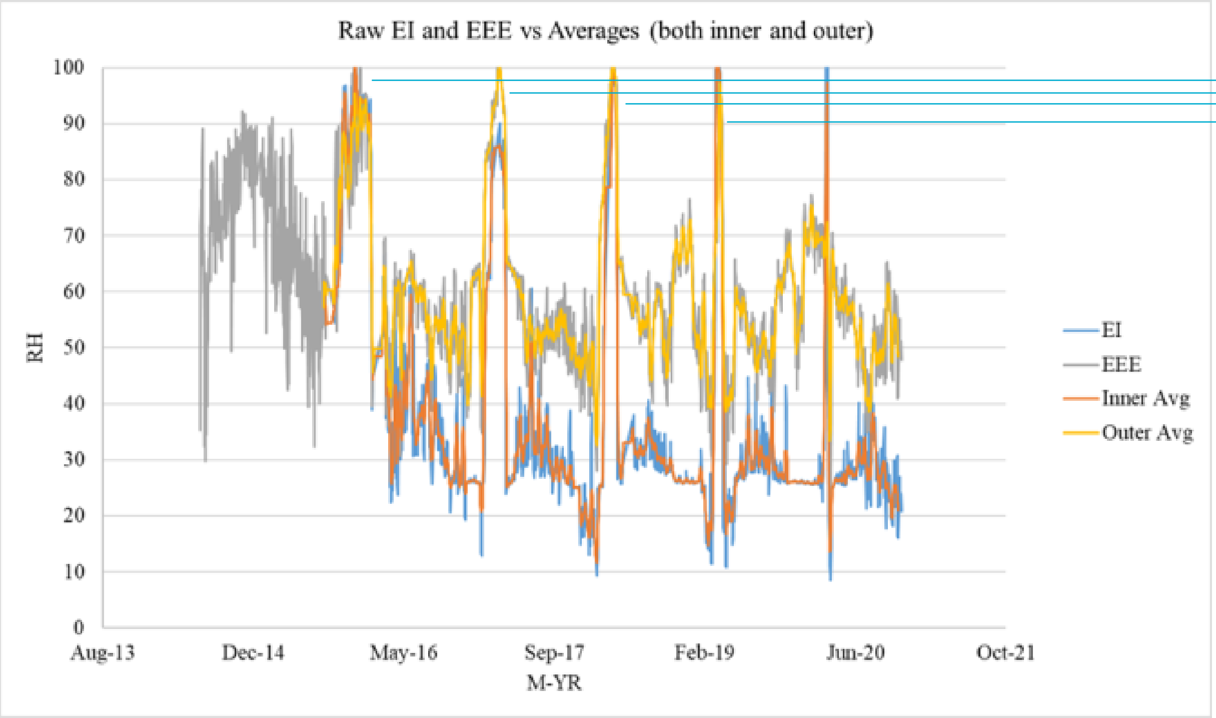
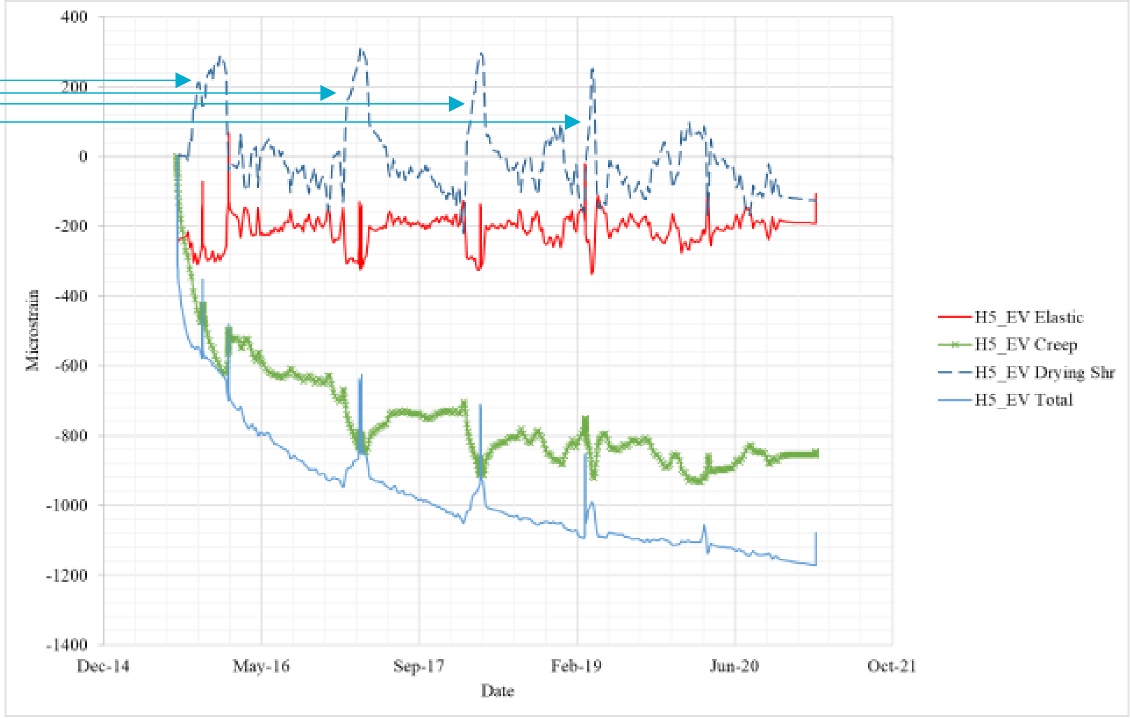
Results: Drying Shrinkage Response to RH Changes

- Rises in RH in the CV consistent with rises in CV simulation strains





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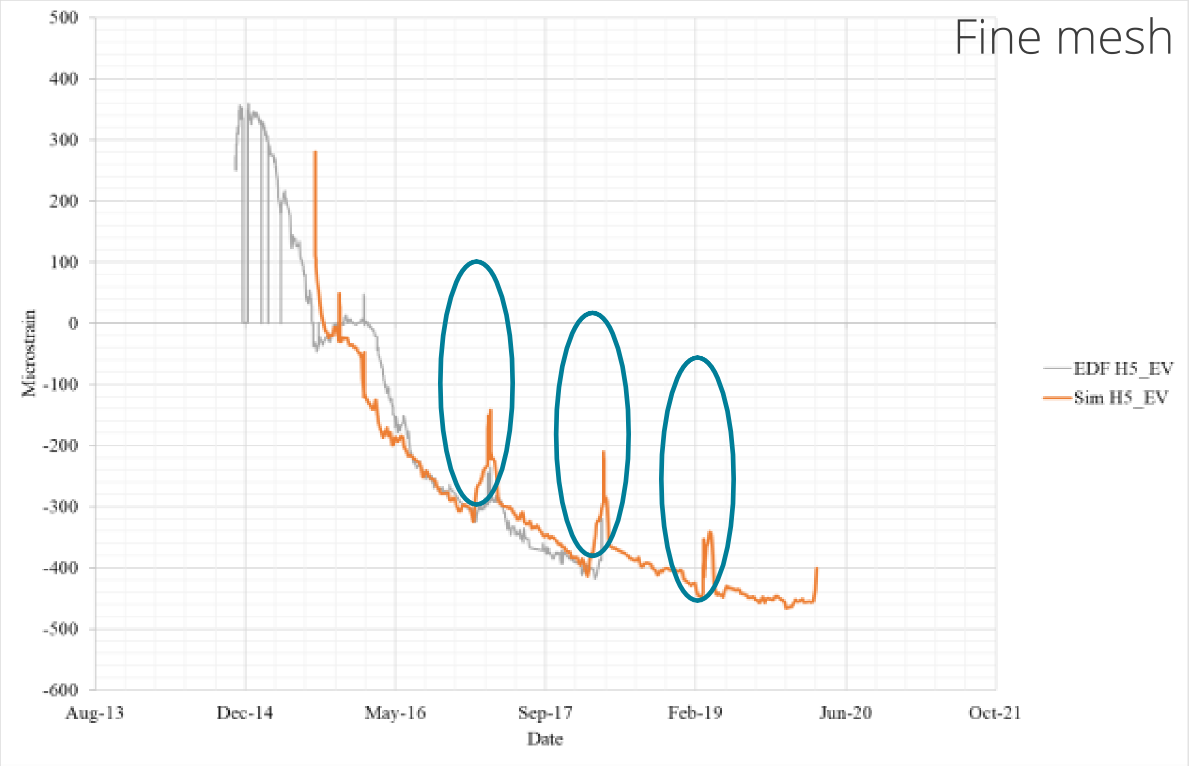
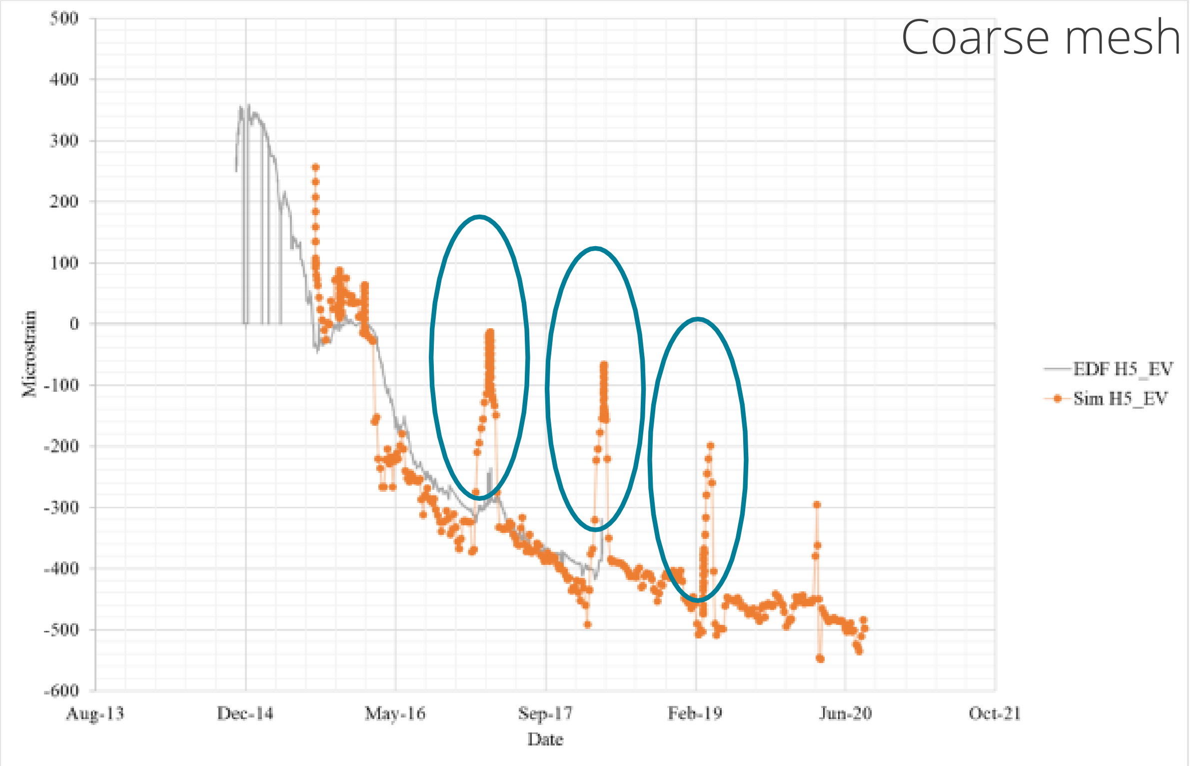
Results: Mesh Sensitivity

- The drying shrinkage response was extremely mesh sensitive
- Only investigated spatial sensitivity thus far (time sensitivity not studied yet)
- Spatial resolution effects are similar in magnitude to including phenomena such as creep and shrinkage for the quantity of interest (strain)

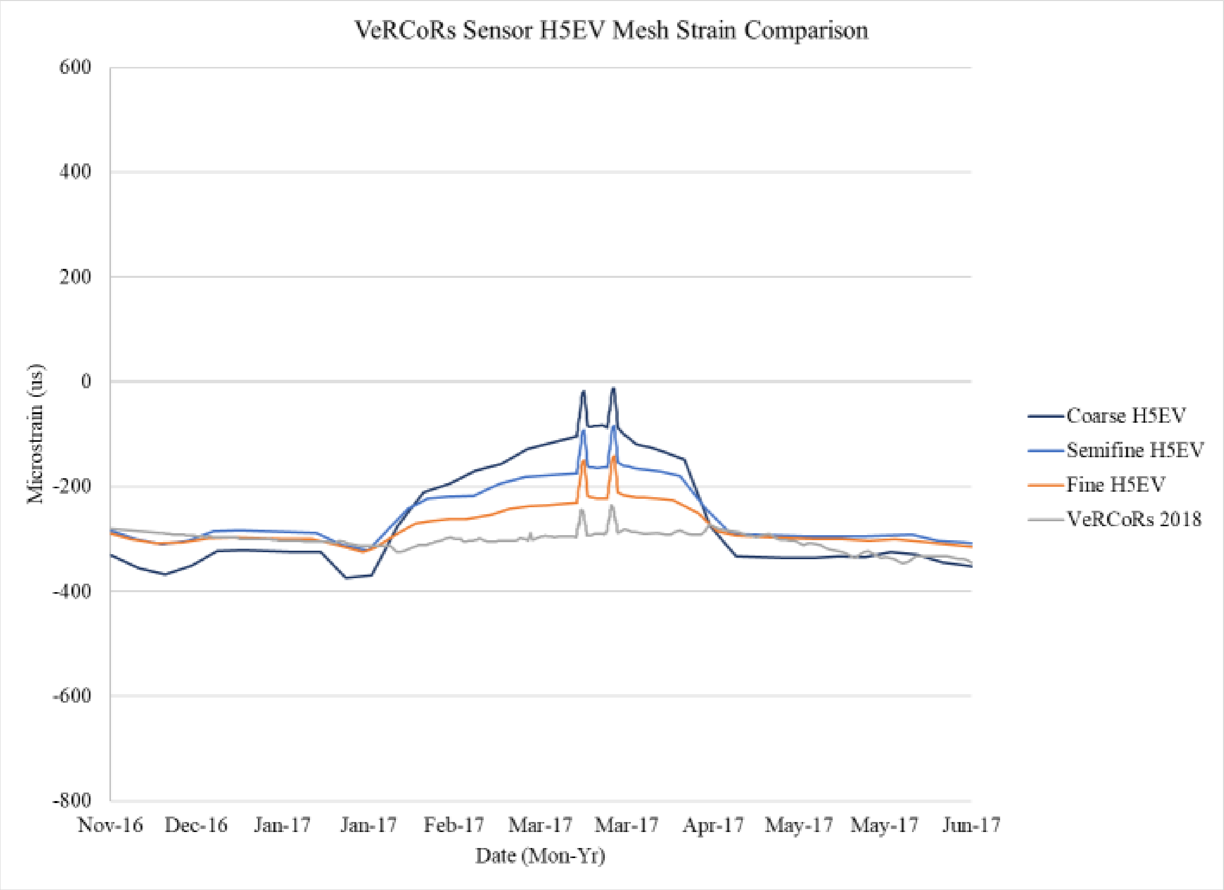




Results: Mesh Convergence

- Data showed that a finer mesh converged the simulation results towards the experimental data
- Smaller time steps may also affect the results (future work)

Dual pressurization events:
VD1 & VD1 bis



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Conclusions

- Both creep and drying shrinkage concrete material properties in the simulation were essential in fitting the simulation results to the experimental data
- ABAQUS's thermal equation (Fick's 2nd Law) is an acceptable equation for incorporating drying shrinkage properties into concrete, but experimental data is required to fit the coefficients
- Bazant's B3 creep model used experimental creep data to predict the creep response to 80 years
- The drying shrinkage material property was highly sensitive to mesh refinement
- Mesh refinement study indicated a convergence of simulation results towards experimental data