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Coping with Extreme Discretization Sensitivity and Computational Expense in a Solid Mechanics Pipe Bomb Application

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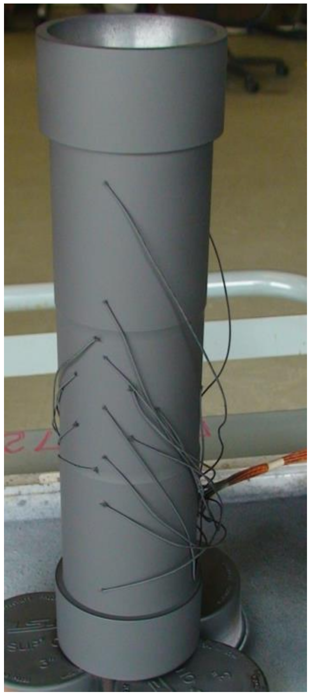
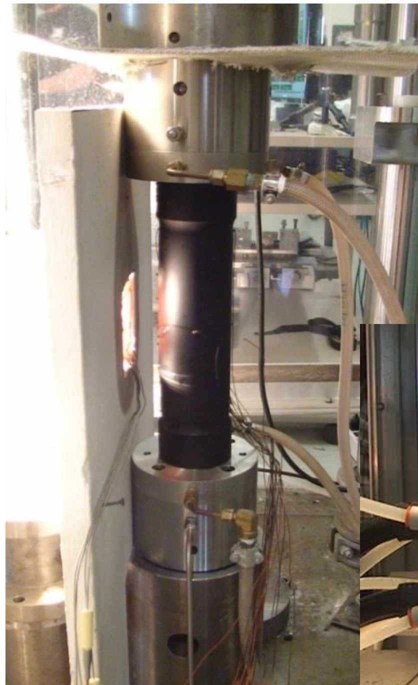
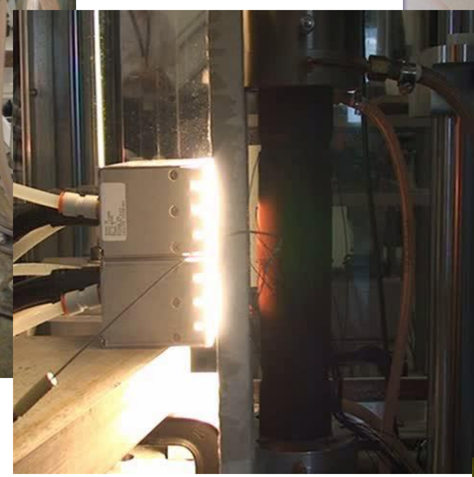
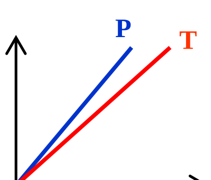
Pipe-Bomb Validation Experiments

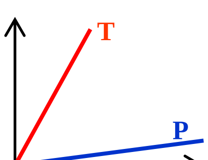


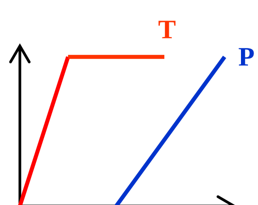




Ramp temperature and pressure independently to failure



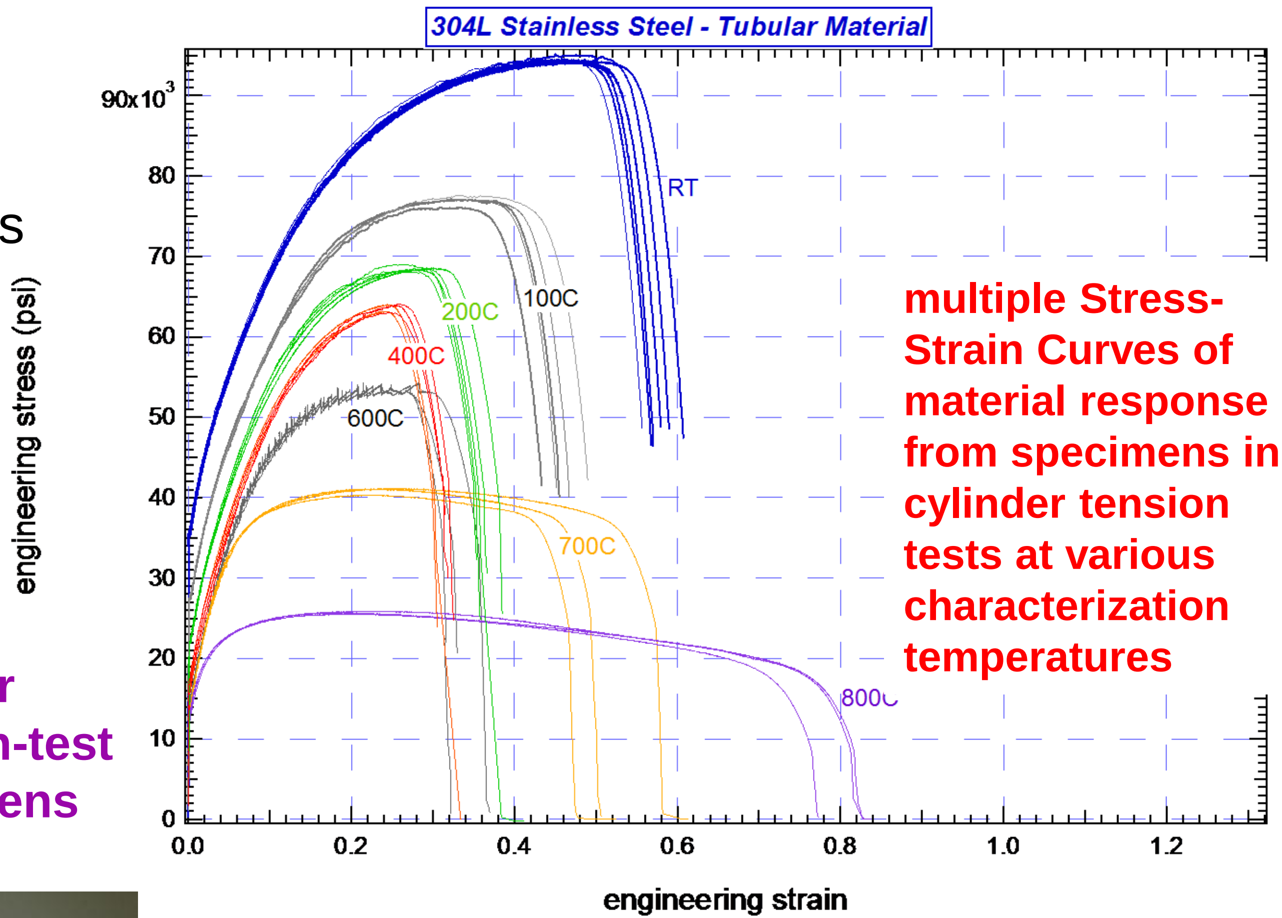




Pipe Material Properties (Experimental)

Ductile Metal
response and failure
in coupon tension tests

304 stainless steel specimens from tube stock



multiple Stress-Strain Curves of material response from specimens in cylinder tension tests at various characterization temperatures

cylinder Tension-test specimens

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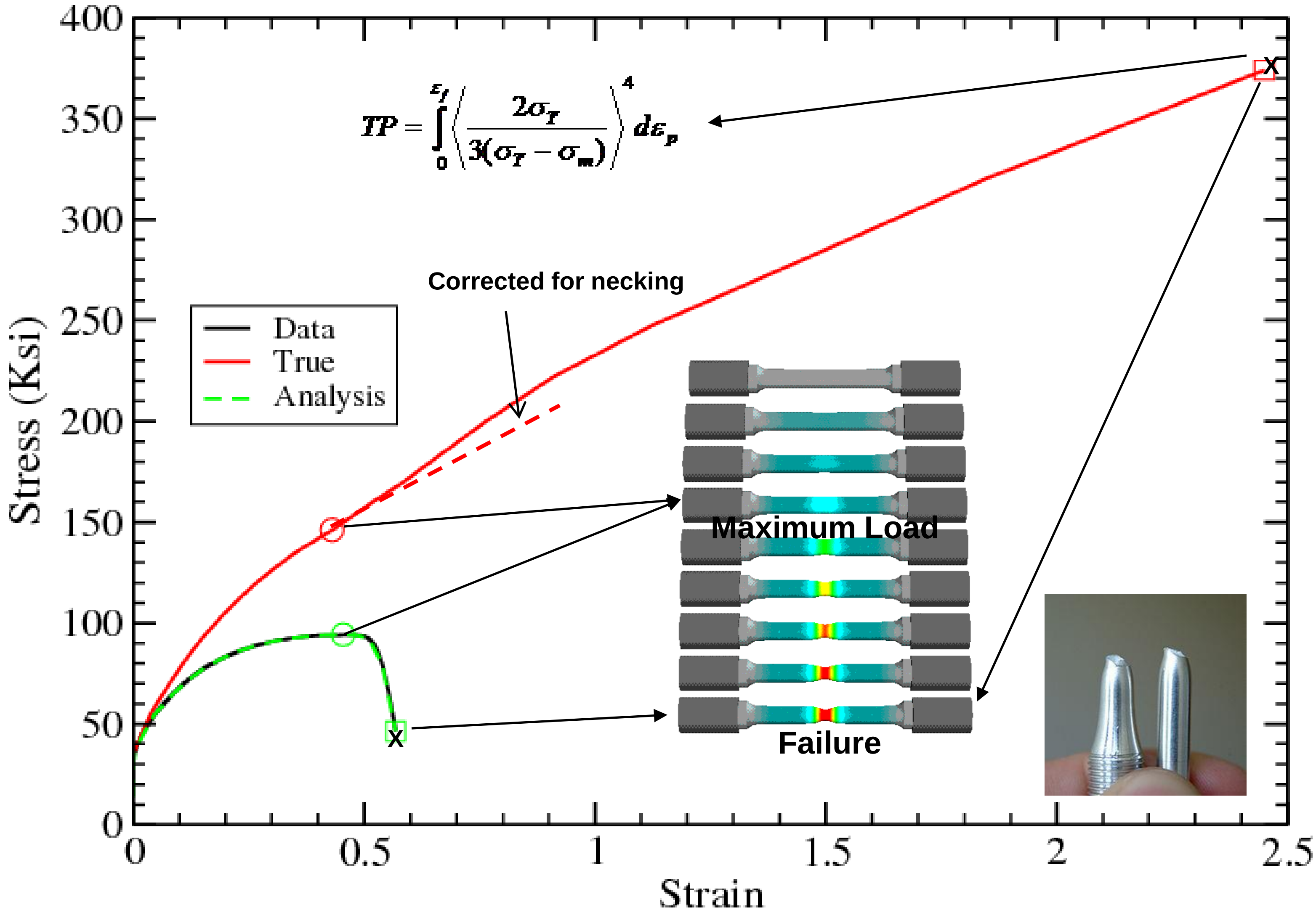
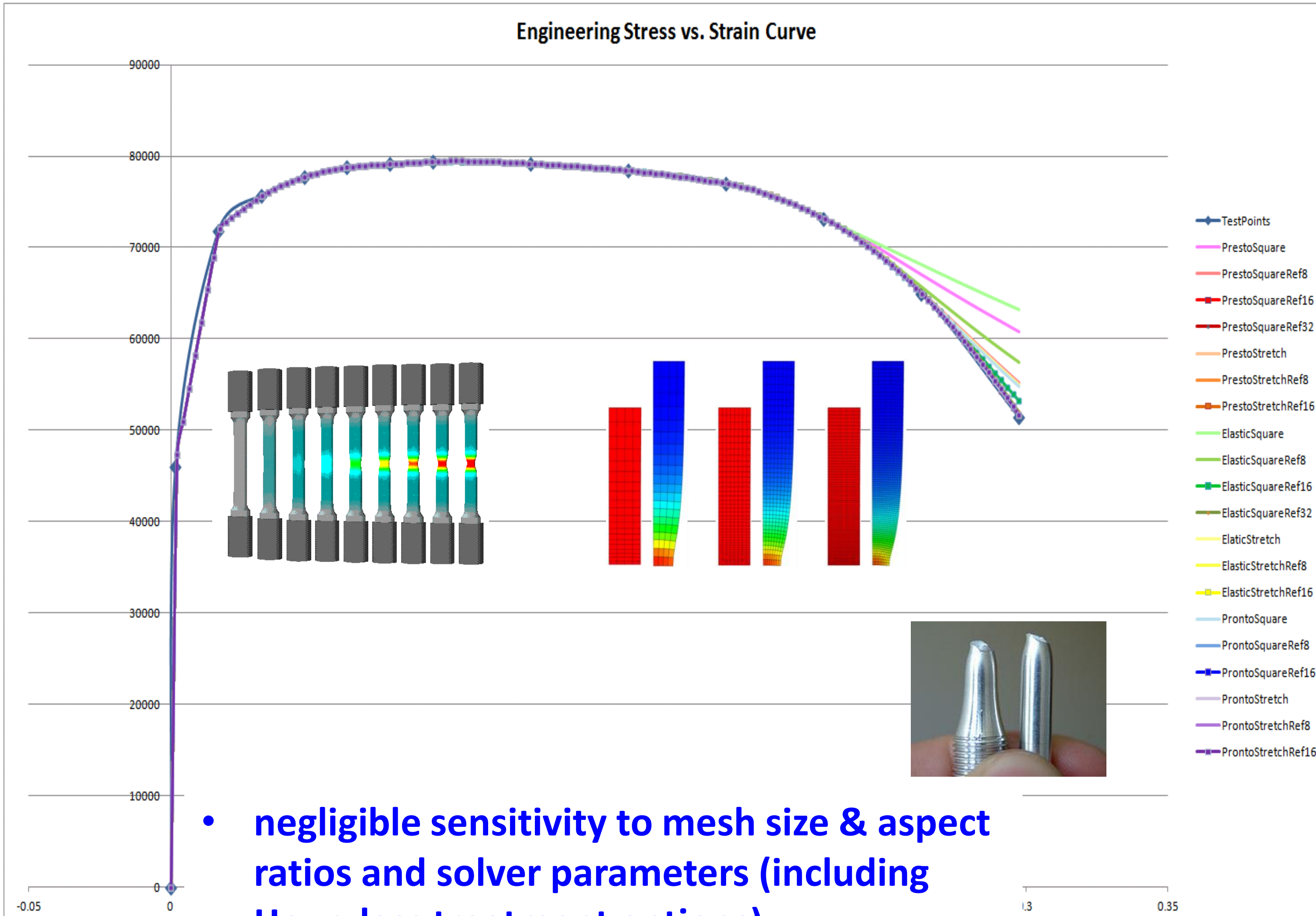
Inversion Procedure to extract constitutive model Cauchy-Stress Logarithmic-Strain Curves from Measured Stress-Strain Behavior in Experiments



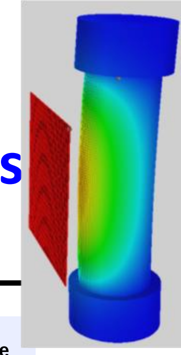
Mesh and Solver Sensitivity Study in modeled cylinder necking/failure in tension tests

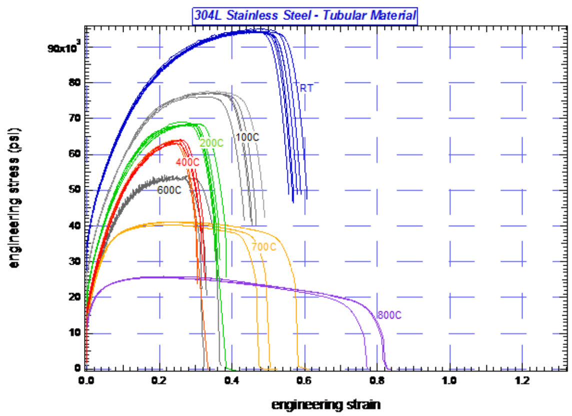


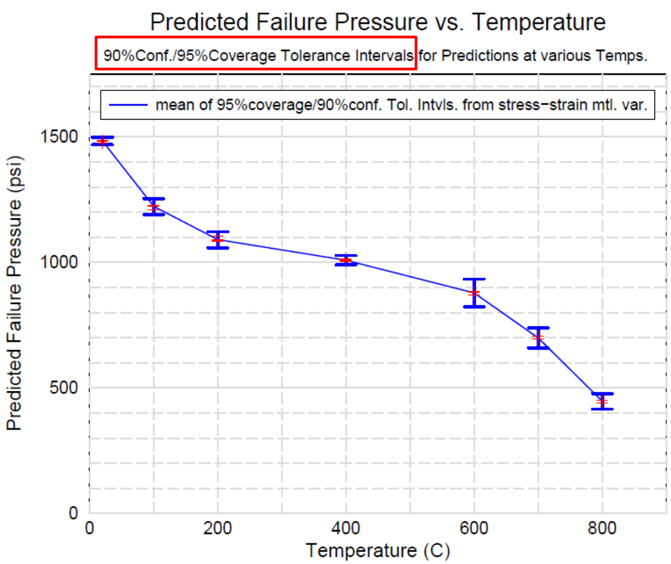
- negligible sensitivity to mesh size & aspect ratios and solver parameters (including Hourglass treatment options)
  in portion of material curves traversed in Pipe bomb calculations

Predicted Range of Pipe-Bomb Failure Pressures due to Variability of Material Stress-Strain Curves at Tested Temps

(Each curve ➡ a run of pipe bomb model)



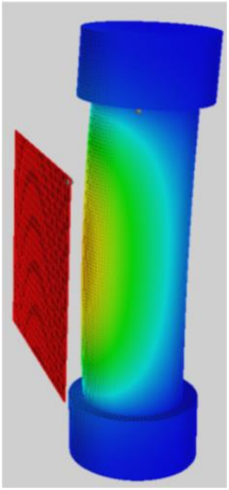


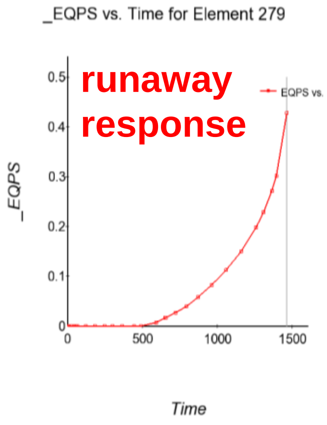


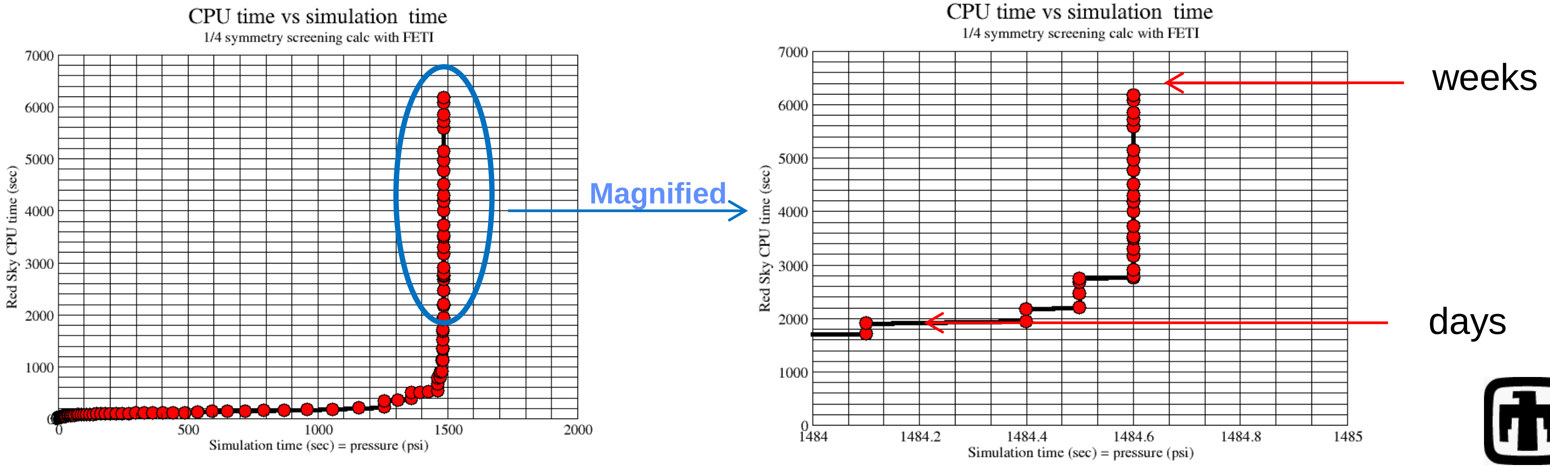
Case	T_max	P_max (psi)	dt (sec)	EQPS_max *	Status	# Procs	cpu-hrs	res	Adaptive
try3-rt	20	1484.5	1.60E-11	0.601		192	0.368	1.00E-06	feti
try4-rt	20	1482.8	9.00E-13	0.571		192	0.308	1.00E-06	feti
try5-rt	20	1485.2	9.00E-13	0.575	high	192	0.324	1.00E-06	feti
try6-rt	20	1485	9.00E-13	0.549		192	0.348	1.00E-06	feti
try39-rt	20	1483.9	9.00E-13	0.587		192	0.402	1.00E-06	feti
try40-rt	20	1474.8	9.00E-13	0.555	Low	192	0.309	1.00E-06	feti
try14-100	100	1227.1	1.00E-11	0.586	High	192	0.441	1.00E-06	feti
try15-100	100	1208.7	9.00E-13	0.528	Low	192	0.546	1.00E-06	feti
try16-100	100	1225.3	9.00E-13	0.561		192	0.31	1.00E-06	feti
try36-100	100	1226.3	8.60E-12	0.559		192	0.335	1.00E-06	feti
try37-100	100	1222.9	1.60E-08	0.549		192	0.284	1.00E-06	feti
try11-200	200	1102.1	1.70E-09	0.529	High	192	0.335	1.00E-06	feti
try12-200	200	1085.8	9.00E-13	0.426		192	2.62	1.00E-06	feti
try13-200	200	1088.6	1.30E-06	0.469		192	2.26	1.00E-06	feti
try34-200	200	1089.9	9.00E-13	0.442		192	0.453	1.00E-06	feti
try35-200	200	1081.7	9.00E-13	0.402	Low	192	0.342	1.00E-06	feti
try17-400	400	1010.3	1.00E-12	0.394		192	0.393	1.00E-06	feti
try18-400	400	1007.2	1.00E-12	0.386		192	0.325	1.00E-06	feti
try19-400	400	1005.7	3.00E-09	0.432		192	0.312	1.00E-06	feti
try32-400	400	1001.9	1.00E-12	0.373	Low	192	2.479	1.00E-06	feti
try33-400	400	1014	1.00E-12	0.384	High	192	0.369	1.00E-06	feti
try22-600	600	869.2	1.00E-12	0.409	Low	192	0.361	1.00E-06	feti
try23-600	600	880.1	4.00E-07	0.49		192	2.54	1.00E-06	feti
try24-600	600	884.7	1.20E-09	0.523	High	192	0.359	1.00E-06	feti
try25-700	700	705.1	1.00E-12	0.617	High	192	0.431	1.00E-06	feti
try26-700	700	694.8	1.00E-12	0.605	Low	192	0.431	1.00E-06	feti
try27-700	700	695.5	1.00E-12	0.606		192	0.443	1.00E-06	feti
try29-800	800	448	3.50E-11	0.501		192	0.476	1.00E-06	feti
try30-800	800	440.8	1.00E-12	0.632	Low	192	0.431	1.00E-06	feti
try31-800	800	448.8	1.00E-12	0.645	High	192	0.414	1.00E-06	feti

Pipe Bomb Simulation Difficulties

- **Pipe wall failure indicated when the quasi-static calculations reach a physical instability point**
  - when the internal pressure exceeds the material's resisting force no static equilibrium is attainable and no inertia terms to stabilize the calculation through breakup
- **large sensitivity to mesh and solver settings**
- **excessive run times**
- **highly distorting elements**







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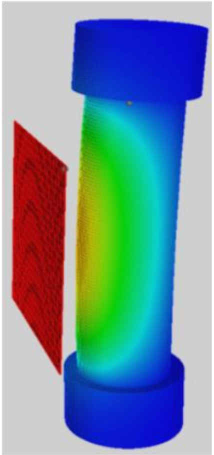
Solver Accuracy and Speed Assessment for Accurate Curve “Strength” Rankings

Test & temperature cases	CG 10^{-6} Failure psi (CPU time*)	FETI-CG 10^{-4} Failure psi (CPU time*)	FETI-CG 10^{-5} Failure psi (CPU time*)	FETI-CG 10^{-6} Failure psi (CPU time*)
try26-700C	704.0 (40.30)	702.0 (20.3)	703.8 (5.87)	703.7 (5.24)
try27-700C	704.9 (40.29)	704.1 (19.1)	704.2 (5.28)	704.2 (6.21)
try3-20C	1485.9 (21.1)	1490.70 (12.1)	1484.5 (7.8)	1484.5 (9.78)
try6-20C	1486.3 (15.2)	1487.20 (4.6)	1485.0 (2.9)	1485.0 (4.39)
try5-20C	1486.4 (16.0)	1492.60 (41.3)	1485.2 (20.7)	1485.2 (8.26)

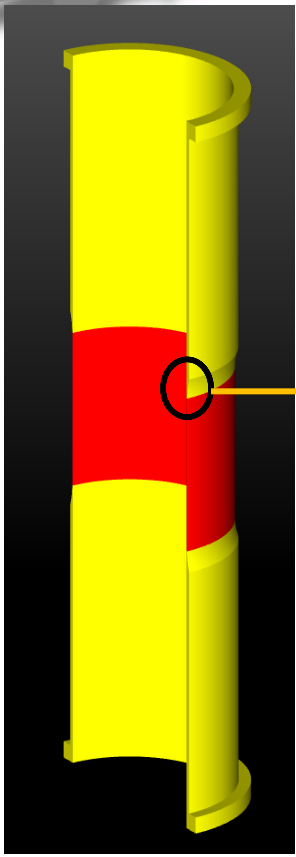
* CPU times reported in Adagio output file via global output variable *cpu_time*. CG and FETI sims. were run on 192 processors of Red Sky

- **Results effectively unchanged when solver tolerance is changed from 10^{-5} to 10^{-6} (for 4tt mesh).**
- **CPU time not >> for 10^{-6}**
- **Use 10^{-6} for production calcs.**

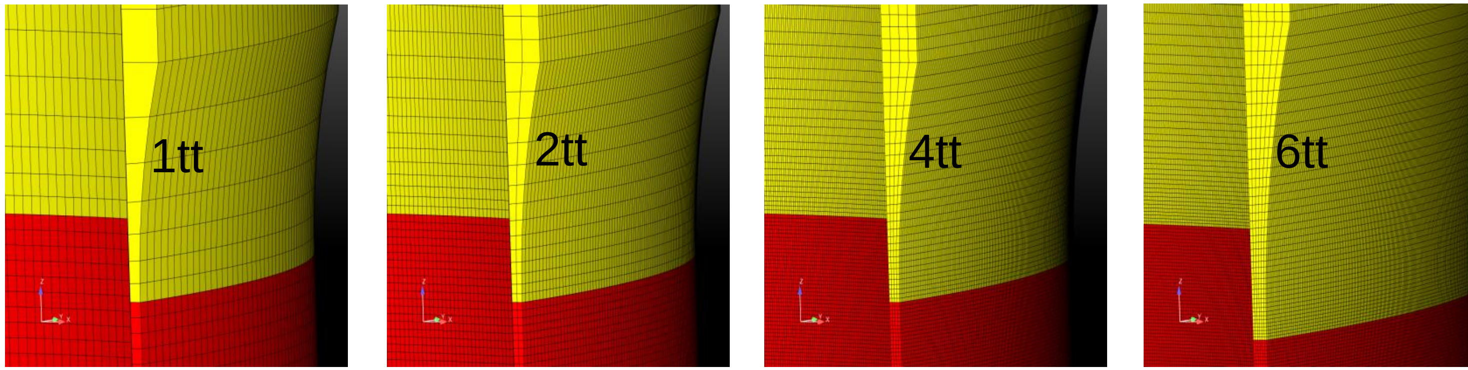
- **Various hourglass treatments also investigated**
- **verified to not have significant effect on predicted failure pressures**



Pipe Bomb Calculation Verification
Mesh Refinement Studies



Pipe model



Geometrically similar **meshes**

Number of Elements thru thickness of wall	1	2	4	6
# Elements (1/4 model)	32,368	276,080	2,173,600	7,458,912
Pressure at Fail (psi)	1069	873	818.3	818.7* (*didn't finish, 16 days on 400cpu's)

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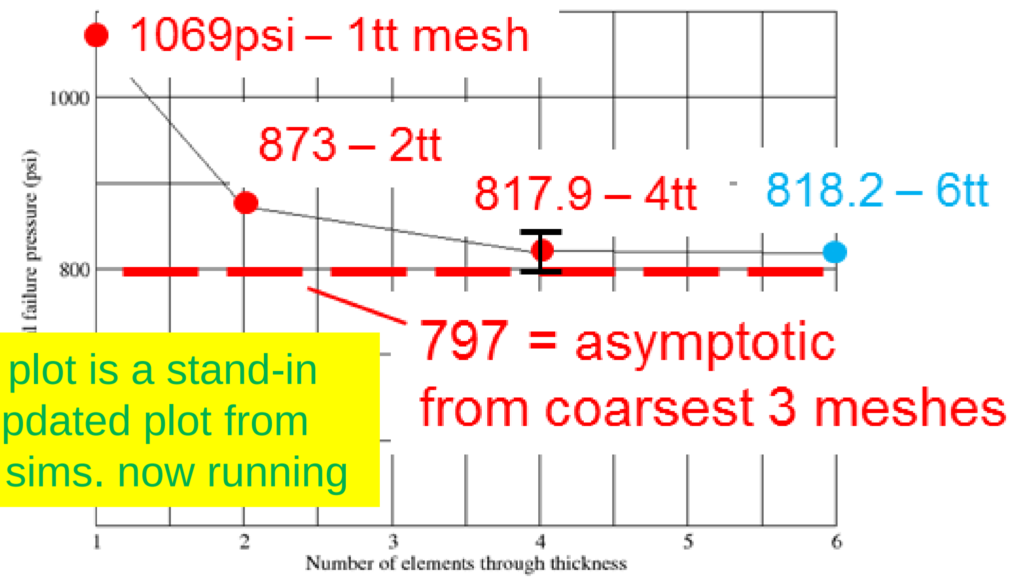
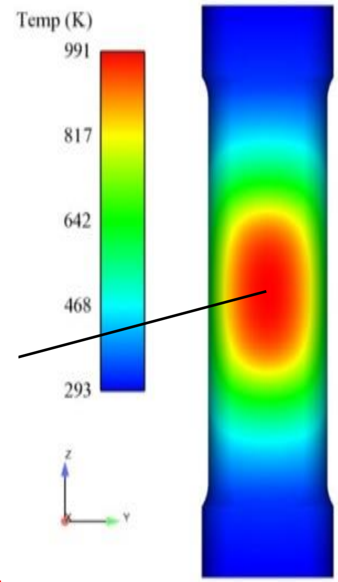
Calculation Verification
Mesh Study Results

Calculated Failure Pressures



- This plot is a stand-in for updated plot from new sims. now running



Other calculated damage quantities not as well behaved due to element/mesh deformations

- **Von Mises stresses**
- **Tearing parameters**
- **Equivalent plastic strain**

- **Coarsest 3 meshes => 1.8 empirical order of convergence**
- **estimate for numerical solution uncertainty: ± 21psi = ± 2.5% of P_{fail} on 4tt mesh**

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Coupled Thermo-Mechanical simulations help Design Experiments and Thermocouple Locations to Reconstruct Temperature Field by Interpolation

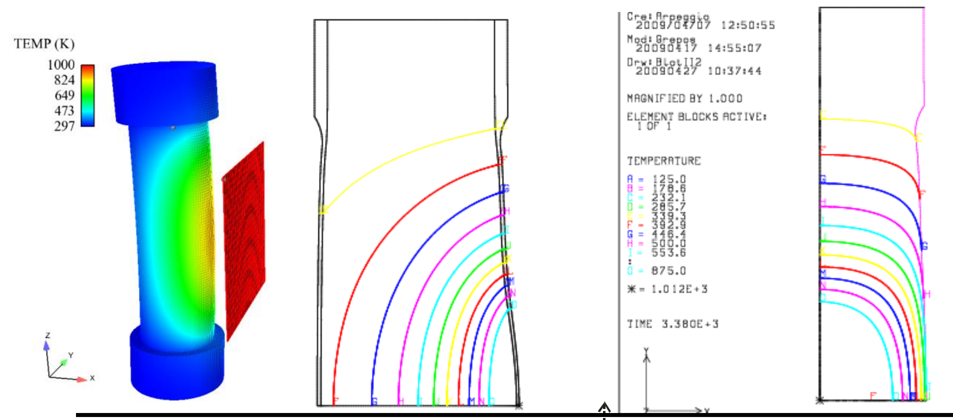
Model

- Pipe radiatively heated by plate
- Convection neglected
- Viewfactors change as pipe bulges toward plate at hot spot

Temperature Contours

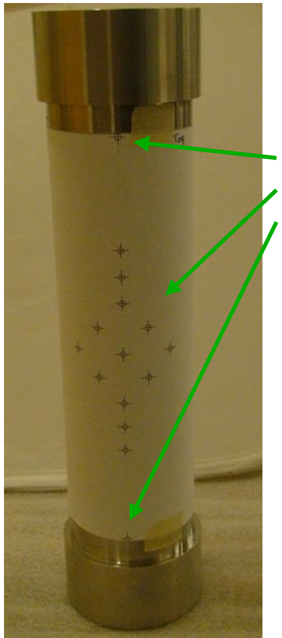
Side view, top half of pipe

Front view, ¼ symmetry



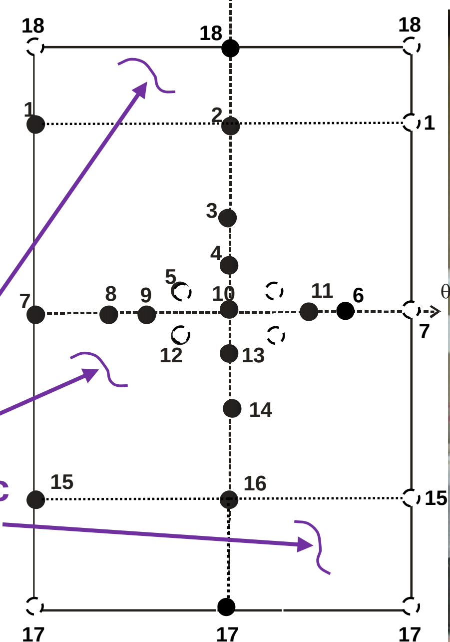
Experiment Design Quantities

- Size & location of plate relative to pipe
- # of thermocouples and locations to adequately reproduce temperature field on pipe surface
- in conjunction with design of interpolation method



Thermocouples (23 total, front & back)

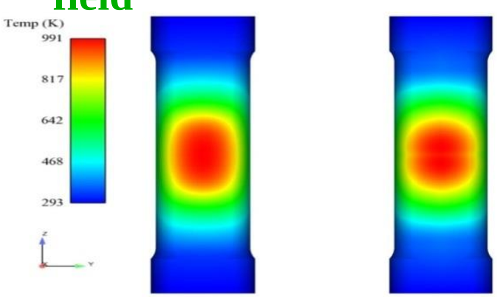
8 Linear to Cubic interpolation patches (C^0 continuous)



Significant Uncertainties in the Model Validation Problem

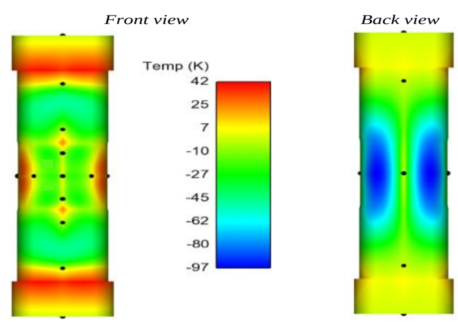
- **material property variability (temperature dependent)**
- **pipe-wall thickness variability**
- **discretization related solution error**
- **uncertainty due to error in temperature BC mapped/interpolated from TCs**
  - **used the coupled thermal-mechanical model in a “nearby” problem to estimate and correct the interpolation bias error with estimated uncertainty in the bias correction**

exact temperature field



interpolated temperature field

interpolation error is zero at TC locations and where yellow fades to green



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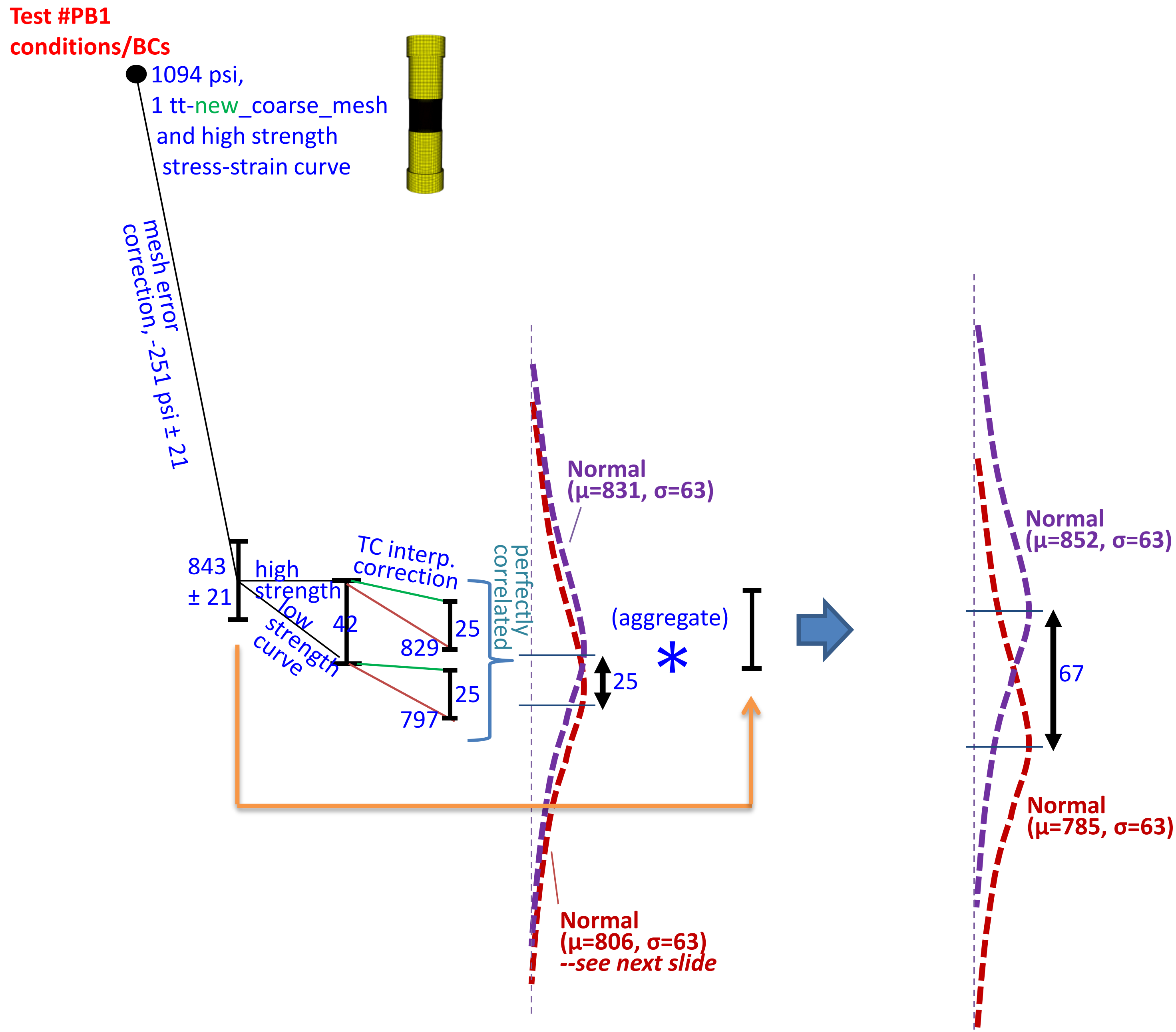
Simulation UQ Rollup



Concluding Remarks

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- **Experimental failure pressures were similarly cast as segregated aleatory and epistemic uncertainties (P-Box representations) for Real Space validation comparisons (Real Space approach presented in 2012 ASME V&V symposium)**

- **The UQ was made affordable by decoupling and linearizing the UQ sources and by using affordable 1tt coarse-mesh model with discretization bias correction + uncertainty.**

- **These compromises not thought to change the validation conclusions in this case (still being confirmed)**

- **Other solid mechanics problems with *load controlled failures* may have many of the challenging computational and UQ aspects of this problem, and may benefit from the UQ and V&V approaches presented here**