

Probabilistic Risk Assessment of Layered Pressure Vessels

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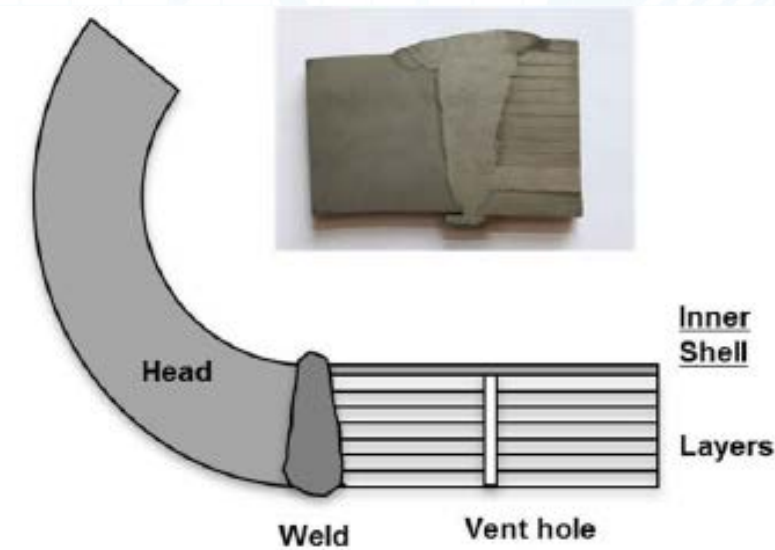
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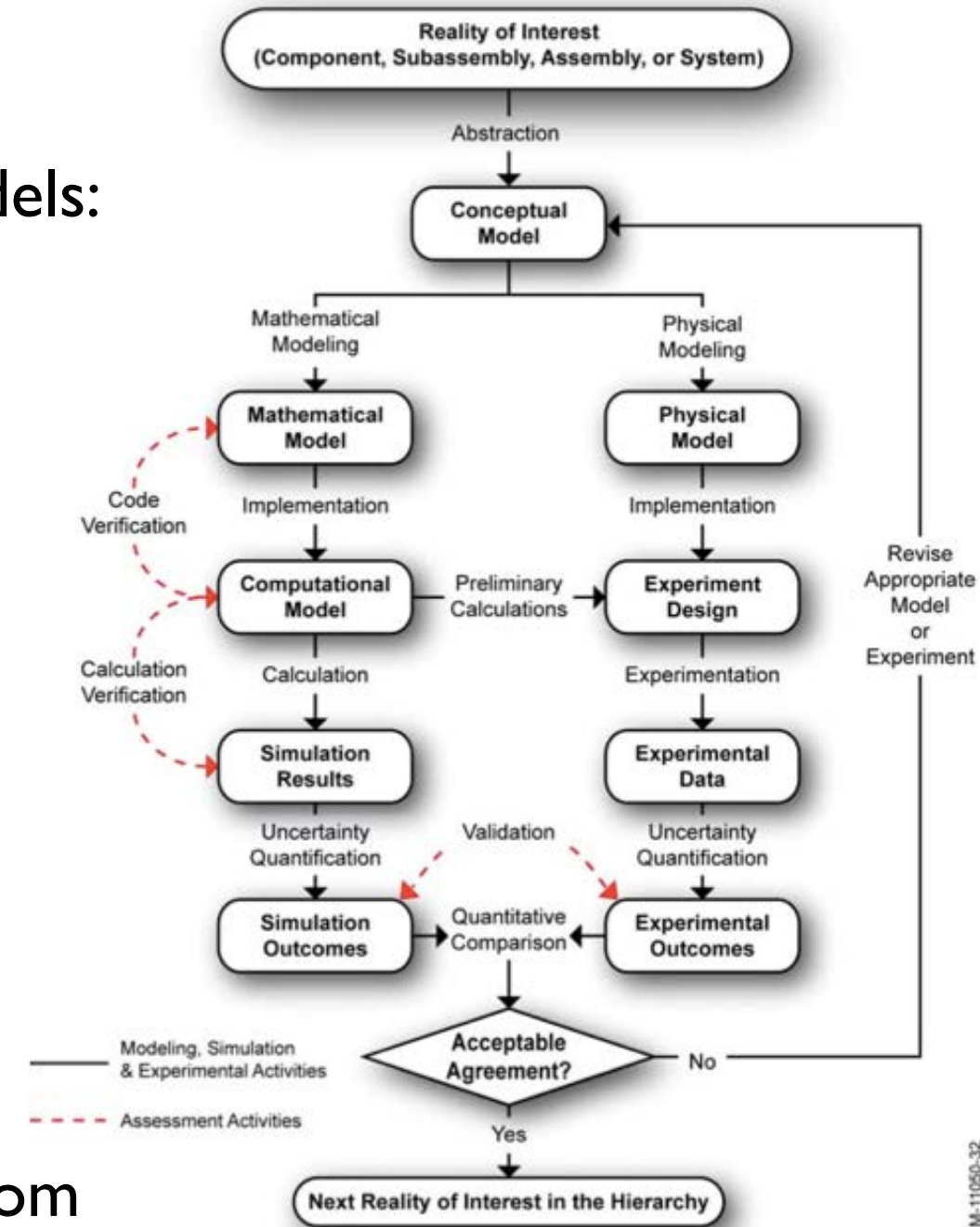
Background and Motivation

- NASA operates ≈ 300 aging layered pressure vessels (LPVs) that were fabricated prior to ASME B&PV code requirements
- Performing traditional fitness for service is challenging and may be overly conservative due to many unknowns in these LPVs:
 - Use of proprietary materials in fabrication
 - Missing construction records
 - Geometric discontinuities
 - Weld residual stress (WRS) uncertainty
 - Complex service stress in and around welds
- **Developed probabilistic framework that can capture variability and uncertainty in LPV fleet and assess risk of fracture in regions of interest**



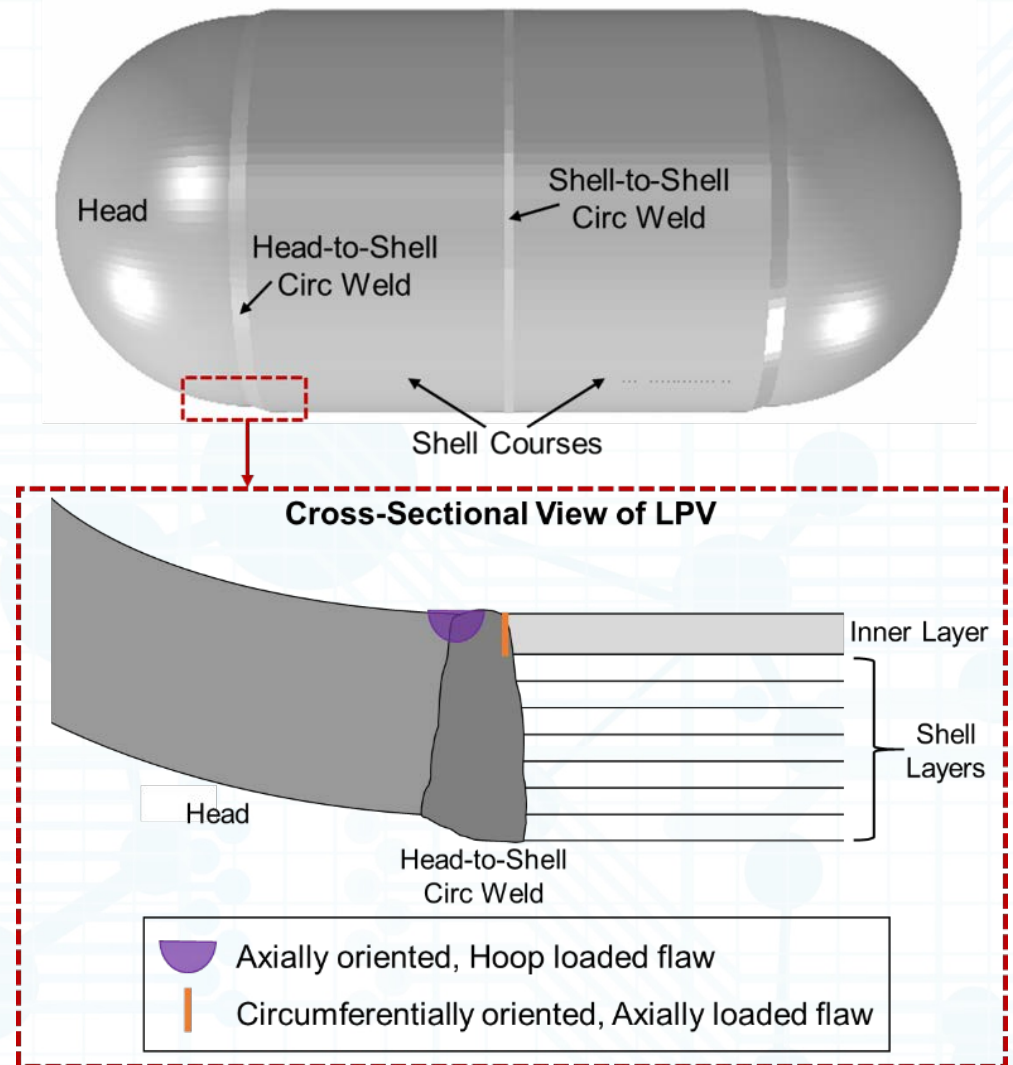
Framework Development

- The probabilistic framework is comprised of multiple models:
 - Vessel geometry
 - Service stress
 - Weld residual stress
 - Stress intensity factor
- Model development was performed using verification and validation (V&V) approach:
 - Identify important phenomena
 - Quantify uncertainties and approximations
 - Establish evidence about predictive accuracy of the models
- NESSUS[®] probabilistic software makes model inputs random variables, exercises the models, and links model outputs



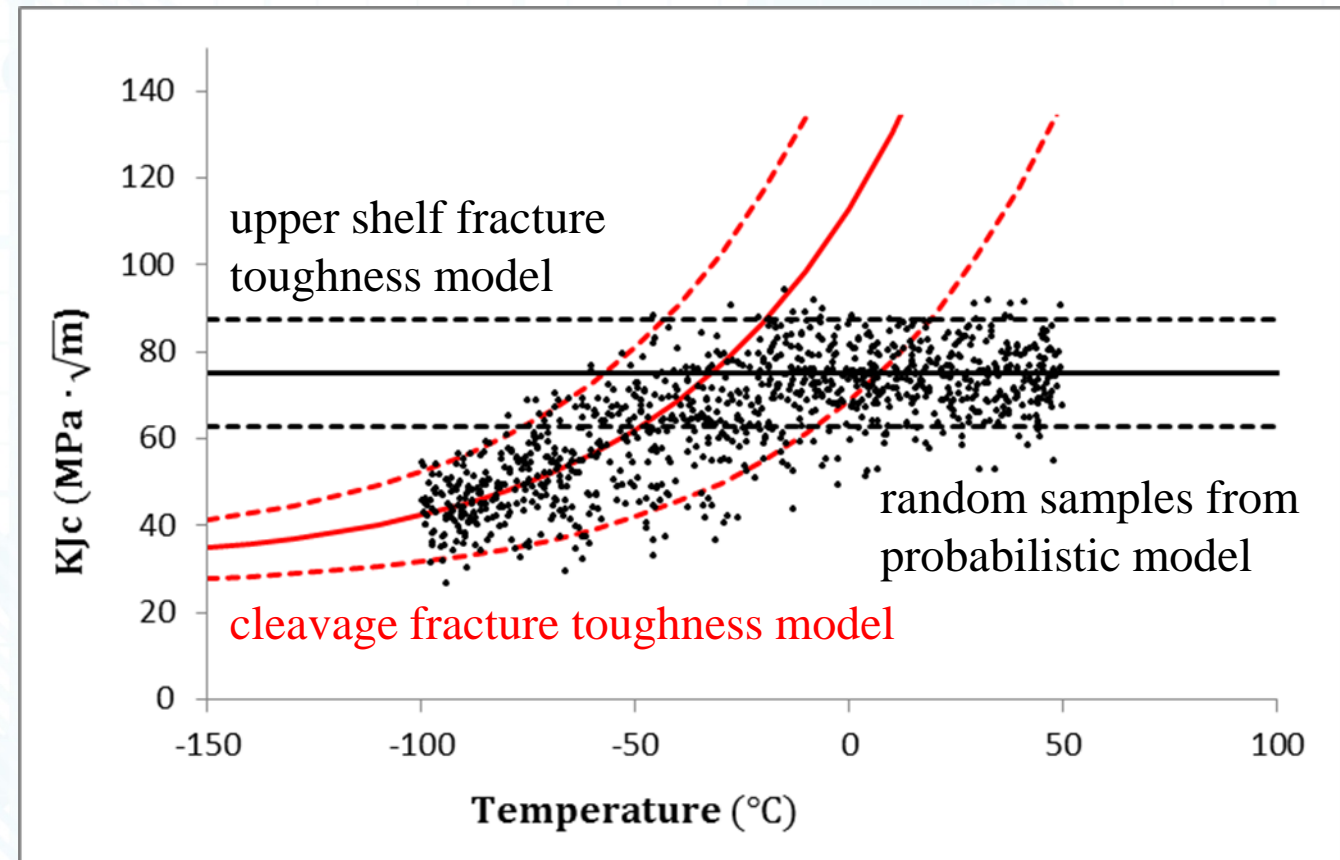
Demonstration Cases and Probabilistic Analysis

- Predict stress intensity factor (SIF) for two flaws in head-to-shell (H-S) circumferential welds for 4-layer (small) and 14-layer (large) LPV to demonstrate framework
 - H-S welds have unique geometry and stress → interlayer gaps introduce bending stress + complex WRS from fabrication
 - H-S weld non-destructive evaluation (NDE) is challenging → use models in probabilistic framework to guide NDE
- Perform probabilistic studies: (1) full cumulative distribution function and (2) global sensitivity analysis
- Compute probability of failure based on limit-state function: $g = K_{JC} - K_I = 0$
 - $p_f = P[g < 0] = P[K_{JC} - K_I < 0] = P[K_{JC} < K_I]$
 - Integrate joint PDF (f_X) of all random variables (X) over failure region: $p_f = \int_{g < 0} \dots \int f_X(x) dx$



Vessel Materials and Geometry

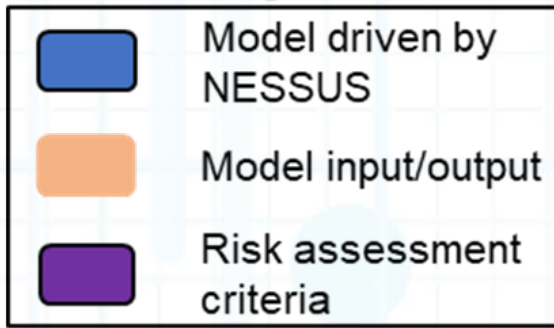
- 4-layer (1 inner + 3 shell layers) and 14-layer (1 inner + 13 shell layers) vessel:
 - Manufactured in 1963 by Chicago Bridge and Iron Company
 - Inner layer rolled from 1143 Mod. steel
 - Shell layers rolled from 1146 steel
 - Head fabricated from A-225 Grade B FBX steel
- Uncertainty in inner shell and head thickness estimated based on construction records
- Variation in vessel efficiency estimated from pi tape measurements of other vessels in fleet
- Fracture toughness determined experimentally
 - ASTM E-1921 → cleavage toughness model
 - Uncertainty in cleavage transition to upper shelf
 - use lower of cleavage or upper shelf toughness



Cleavage and upper shelf fracture toughness models with 5% and 95% tolerance bounds

Probabilistic Framework

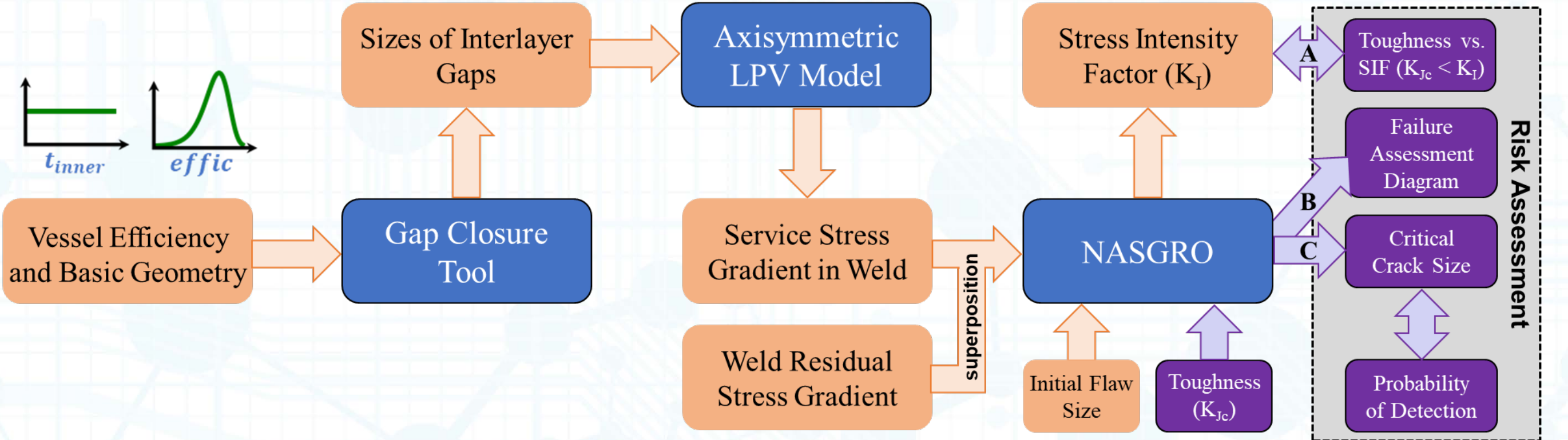
Legend



NESSUS Probabilistic Framework

(B) NASFLA FAD

- Inputs:**
- Service stress
 - Weld residual stress
 - Total thickness
 - Initial crack depth (a_0)
 - Initial crack shape (a/c)
 - da/dN model (C, n)
 - Width of plate (W)
 - Offset (B)
 - Toughness (K_{Jc})
 - Elastic modulus
 - Yield stress
- Output:** Critical crack size, FAD



Vessel Efficiency and Basic Geometry

Gap Closure Tool

Sizes of Interlayer Gaps

Axisymmetric LPV Model

Service Stress Gradient in Weld

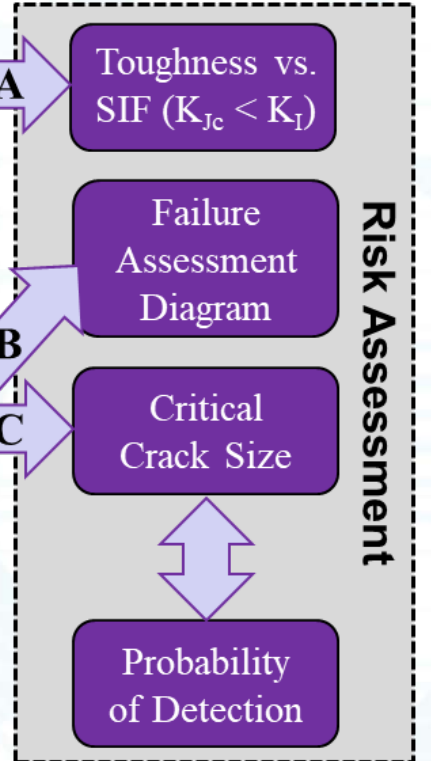
Weld Residual Stress Gradient

Stress Intensity Factor (K_I)

NASGRO

Initial Flaw Size

Toughness (K_{Jc})



Gap Closure Tool

- Inputs:**
- Diameter
 - Pressure
 - Gap type
 - Efficiency
 - Number of layers
 - Inner layer thickness
 - Shell layer thickness
 - Elastic modulus
- Output:** Gap sizes

Parametric Axisymmetric LPV Model

- Inputs:**
- Gap distribution
 - Diameter
 - Pressure
 - Number of layers
 - Inner layer thick.
 - Shell layer thick.
 - Head thickness
 - Circ. weld width
 - Inner layer mod.
 - Shell layer mod.
 - Head modulus
 - Circ. weld mod.
 - Friction
- Output:** Service stress gradient

(A) NASSIF

- Inputs:**
- Service stress gradient
 - Weld residual stress grad.
 - Total thickness of vessel
 - Crack depth (a)
 - Crack shape (a/c)
 - Width of fracture plate (W)
 - Offset from plate center (B)
- Output:** Stress intensity factor

(C) NASCCS

- Inputs:**
- Service stress
 - Weld residual stress
 - Total thickness
 - Initial crack shape (a/c)
 - Width of plate (W)
 - Offset from center (B)
 - Toughness (K_{Jc})
- Output:** Critical crack size

Input Variables for each Model and the **Model Response:**

Gap Closure Tool

- Excel-based tool developed at NASA's Marshall Space Flight Center
 - **Inputs:** basic vessel geometry, linear elastic material properties, vessel efficiency, internal pressure, and through-thickness distribution of gaps
 - **Outputs:** through-thickness size of interlayer gaps and closure pressure
 - Uses thin walled vessel theory and Excel's Goal Seek function
- Uniform through-thickness distribution of gaps used in this study
 - conservative assumption

Input basic vessel parameters

Vessel	d inner	20	in.										
	t total	1.750	in.										
	E	29500000	psi										
	# Layers	6											
	MAWP	5500	psig										
	Gapping Type *	1											
	Target Efficiency	85	Macro										

Given a target efficiency, computes equivalent layer gapping

Layer #	T layer	Gap	R Layer	Mono Equivalent			Layered Response			All	
				T closure	P closure	P closure	R Mono	C closure	D Closure	σ _a (ksi)	P actual
0	0.5	0.000530	10.251	0.500	76.396	87.54	10.250	65.977	21.001	0.230	87.54
1	0.25	0.000530	10.626	0.750	113.331	128.17	10.375	67.551	21.502	0.567	215.71
2	0.25	0.000530	10.877	1.000	149.476	166.85	10.500	69.125	22.003	1.005	382.56
3	0.25	0.000530	11.127	1.250	184.883	203.68	10.625	70.699	22.504	1.540	586.24
4	0.25	0.000530	11.378	1.500	219.602	238.76	10.750	72.273	23.005	2.167	825.00
5	0.25	0.009103	11.637	1.750	4376.813	4675.00	10.875	73.901	23.524	14.450	5500.00
6	0	0.000000	11.762	1.750	0.000	0.00	10.875	73.901	23.524	14.450	5500.00
31	0	0.000000	11.762	1.750	0.000	0.00	10.875	73.901	23.524	14.450	5500.00
Proof	0	0.005355	11.767	1.750	2581.881	2750.00	10.875	73.935	23.534	21.675	8250.00

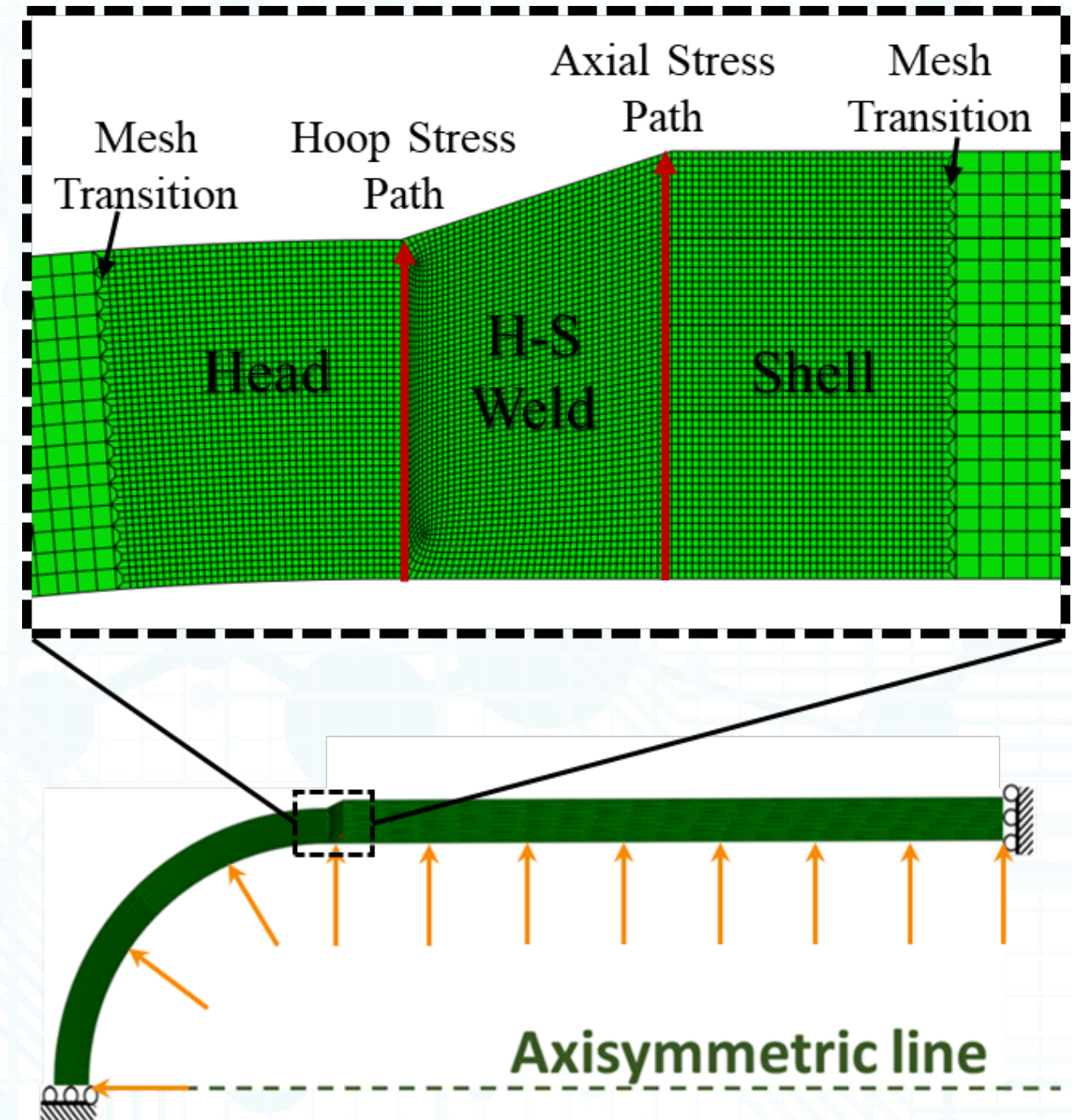
Calculates pressure-consistent stress history for all layers

#	Multiplier	* Gapping Type
1	1	uniform
2	0.5	linear change through thickness
3	0	inner only (most conservative for inner layer)
4	0.8	linear change through thickness
5		

Adjustable presumed gap distribution

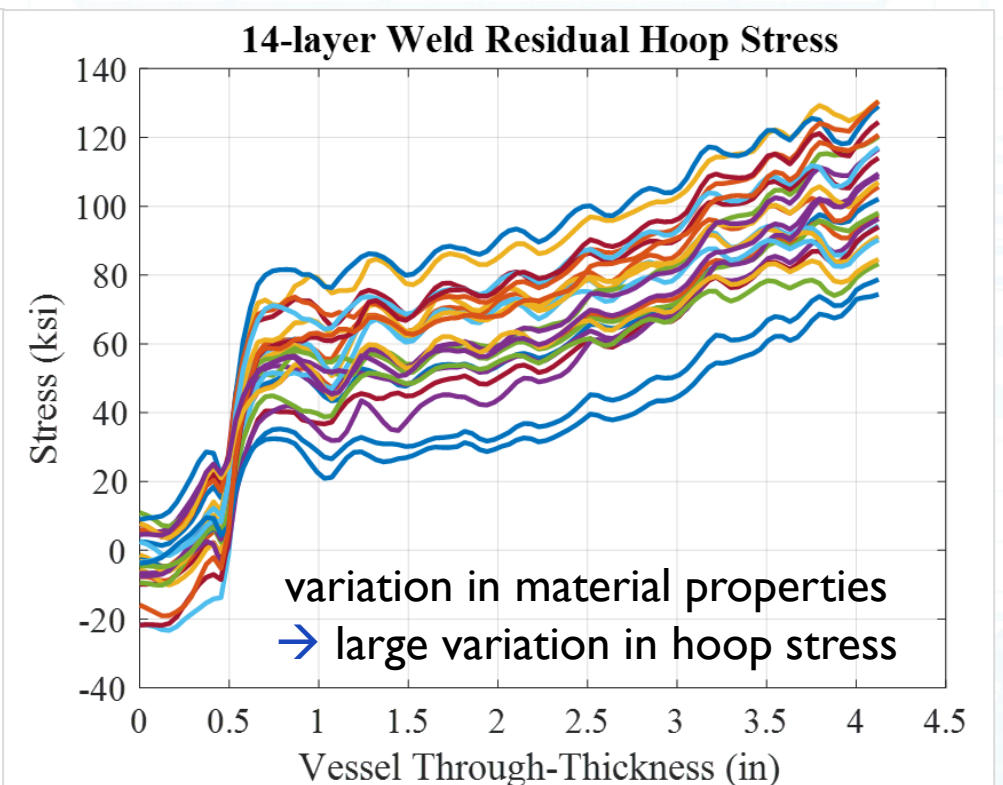
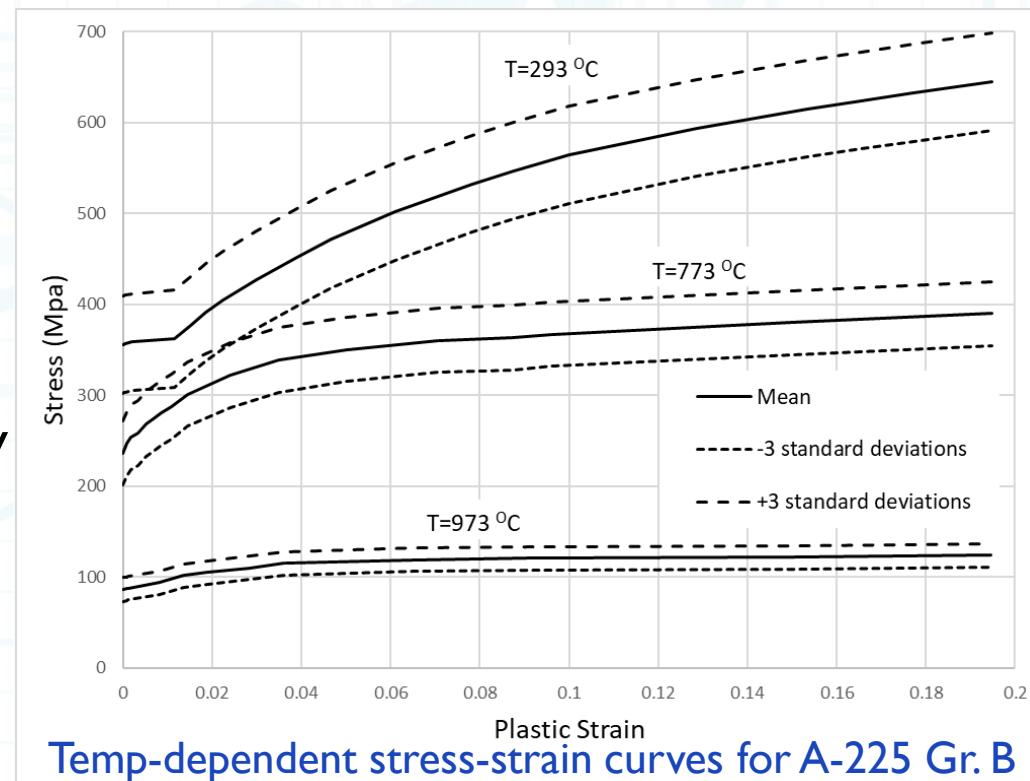
Parametric Axisymmetric LPV Model

- Linear elastic finite element model in Abaqus
 - Parametric → capable of simulating all LPVs in fleet
 - Axisymmetric → takes advantage of axisymmetric nature of circumferential welds to reduce order of simulation and computational cost
 - **Inputs:** vessel geometry, material properties, service pressure, gap sizes from Gap Closure Tool
 - **Outputs:** linear elastic stress field during service (univariate stress gradient extracted along path)
- Limitations of the model:
 - Does not consider effect of longitudinal welds
 - Does not include weld backing plate in geometry



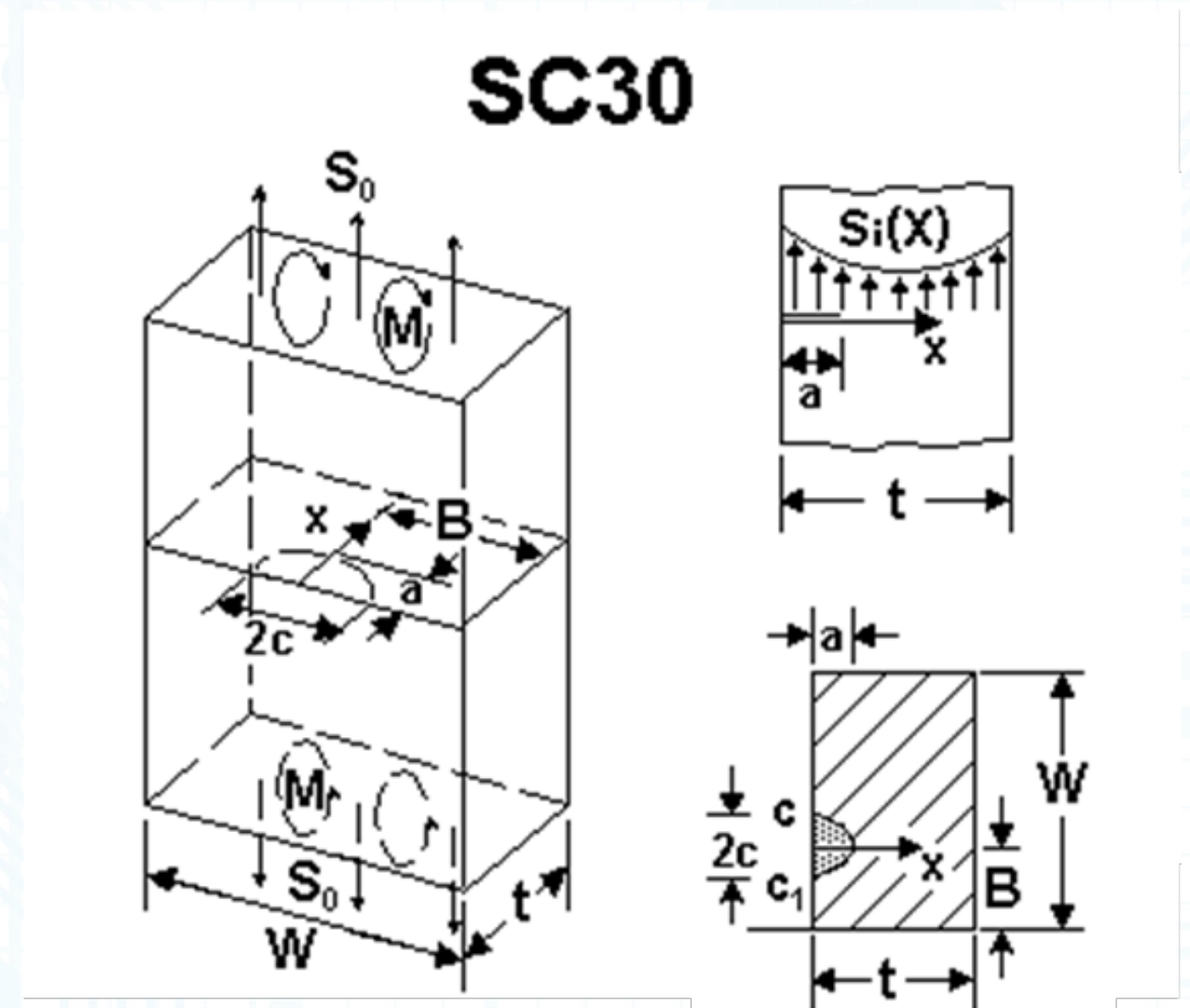
Thermo-mechanical Weld Simulations

- Multi-pass weld simulations of 4- and 14-layer H-S welds performed by Engineering Mechanics Corporation of Columbus using VFT™ (Virtual Fabrication Technology) code¹
 - Sequentially coupled thermo-mechanical FEA → elastic-plastic WRS field prediction
 - Include hydro test at 1.5 times max pressure in simulation → univariate stress gradient extraction after hydro
- Temp-dependent stress-strain curves determined experimentally for materials in vessels
- Temp-dependent CTE and stress-strain curves (yield stress) are random variables
- Generated 25 WRS gradients to train surrogate model
 - PCA-based model
 - Predicts WRS variability
 - Reduces computational cost vs. FEA

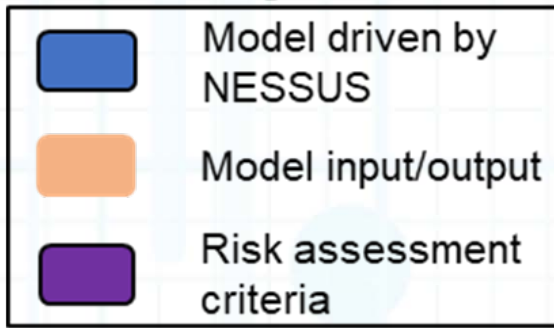


Fracture Mechanics Model

- Used NASGRO[®] fracture mechanics software² to perform LEFM
- Model reference flaws as semi-elliptical surface crack in flat plate (SC30 weight function solution)
- In this study:
 - Width of plate (W) = $\frac{1}{2}$ vessel circumference
 - Thickness of plate (t) = thickness of vessel
 - Cracks centered in the plate ($B = \frac{W}{2}$)
- Univariate service stress and WRS superimposed to create stress field for computing SIF
- NASGRO[®] capabilities include fatigue crack growth, FAD, and CCS



Legend



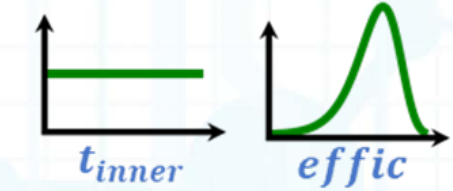
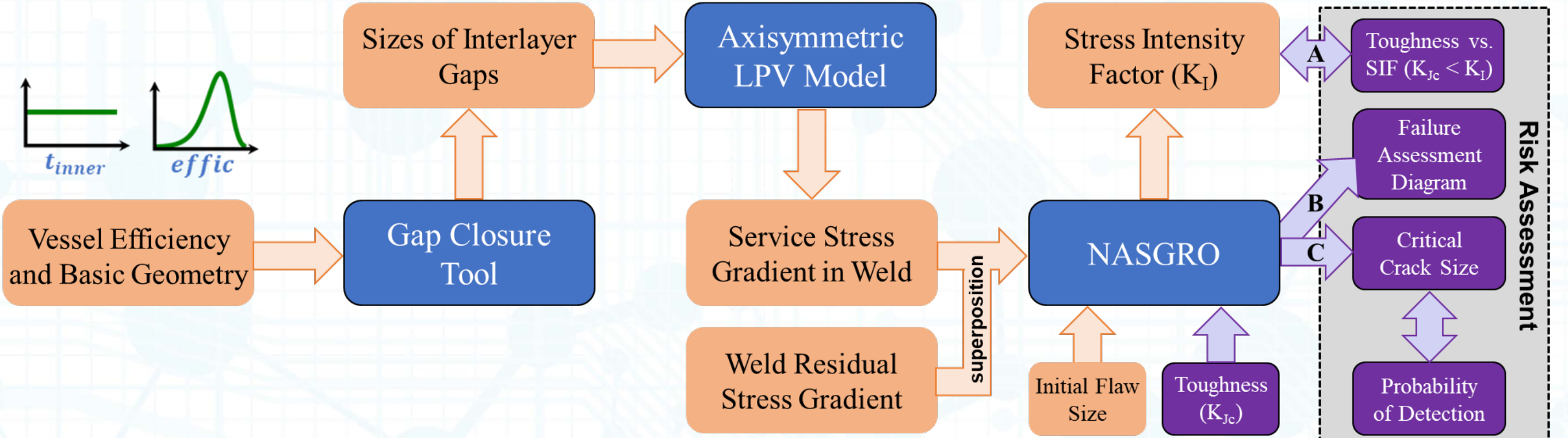
NESSUS Probabilistic Framework

(B) NASFLA FAD

Inputs:

- Service stress
- Weld residual stress
- Total thickness
- Initial crack depth (a_0)
- Initial crack shape (a/c)
- da/dN model (C, n)
- Width of plate (W)
- Offset (B)
- Toughness (K_{Jc})
- Elastic modulus
- Yield stress

Output: Critical crack size, FAD



Gap Closure Tool

Inputs:

- Diameter
- Pressure
- Gap type
- Efficiency
- Number of layers
- Inner layer thickness
- Shell layer thickness
- Elastic modulus

Output: Gap sizes

Parametric Axisymmetric LPV Model

Inputs:

- Gap distribution
- Diameter
- Pressure
- Number of layers
- Inner layer thick.
- Shell layer thick.
- Head thickness
- Circ. weld width
- Inner layer mod.
- Shell layer mod.
- Head modulus
- Circ. weld mod.
- Friction

Output: Service stress gradient

(A) NASSIF

Inputs:

- Service stress gradient
- Weld residual stress grad.
- Total thickness of vessel
- Crack depth (a)
- Crack shape (a/c)
- Width of fracture plate (W)
- Offset from plate center (B)

Output: Stress intensity factor

(C) NASCCS

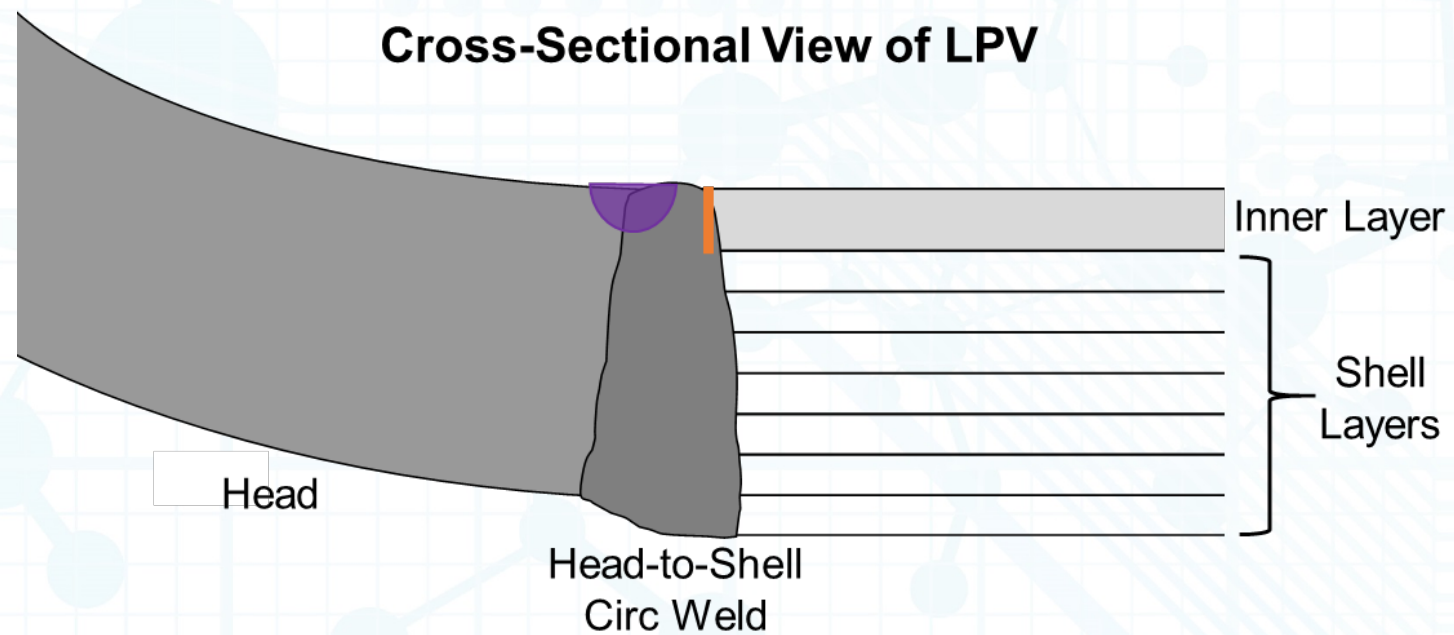
Inputs:

- Service stress
- Weld residual stress
- Total thickness
- Initial crack shape (a/c)
- Width of plate (W)
- Offset from center (B)
- Toughness (K_{Jc})

Output: Critical crack size

Input Variables for each Model and the **Model Response:**



Preliminary Results



Reference Flaw Sizes

$$a = 0.25 \text{ in, } a/c = 1$$

$$a = 0.2 \text{ in, } a/c = 2/3$$

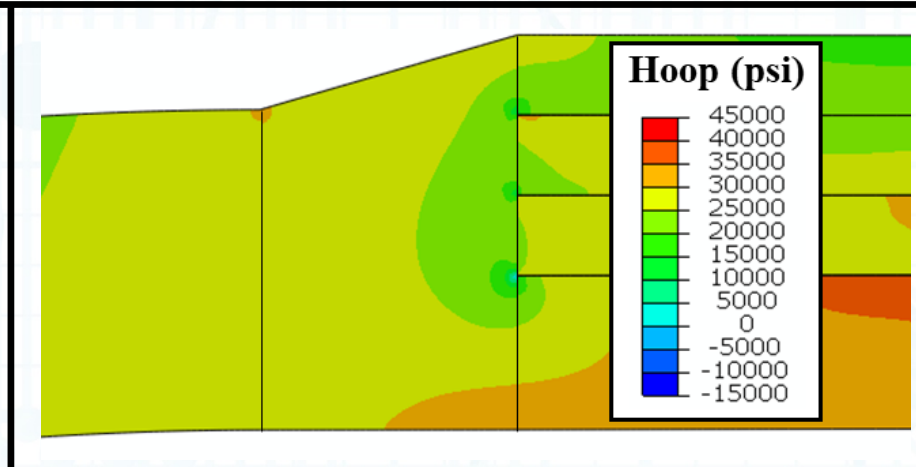
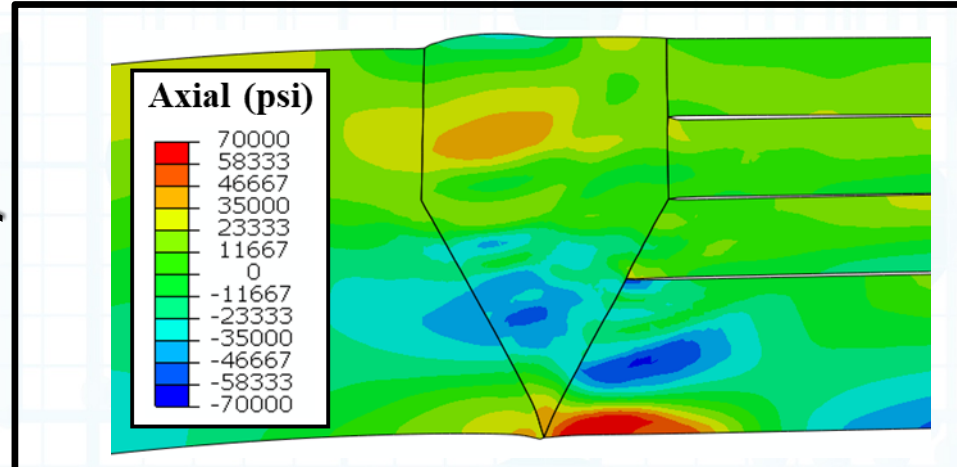
-  Axially oriented, Hoop loaded flaw
-  Circumferentially oriented, Axially loaded flaw

Nominal Stress Plots

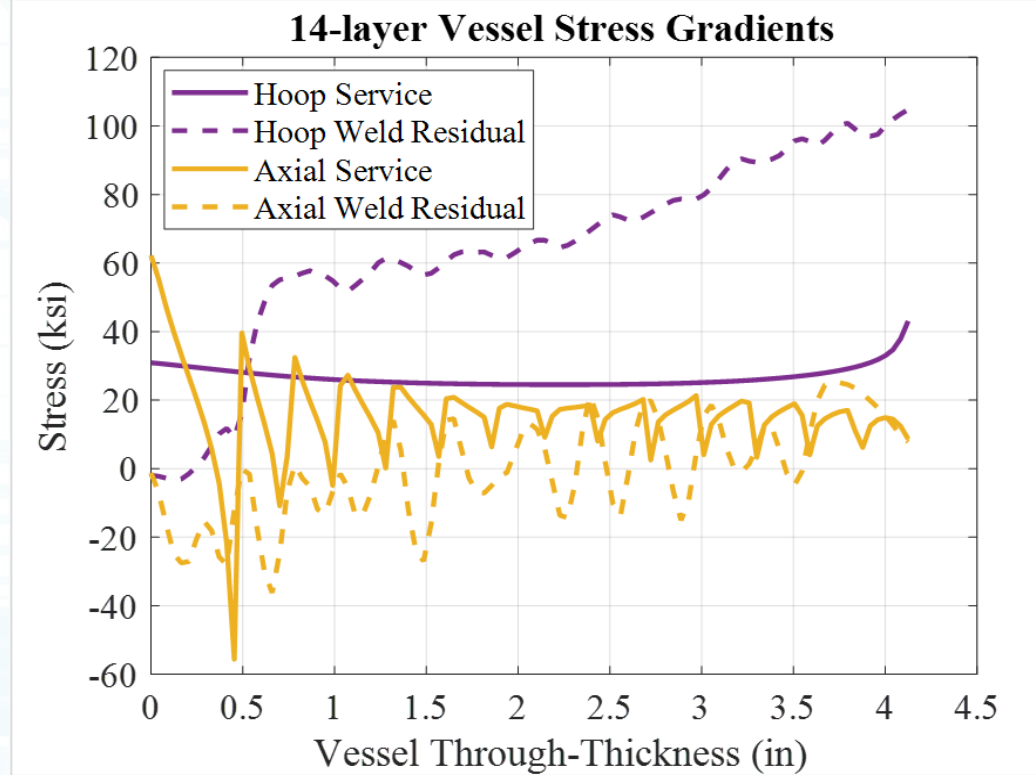
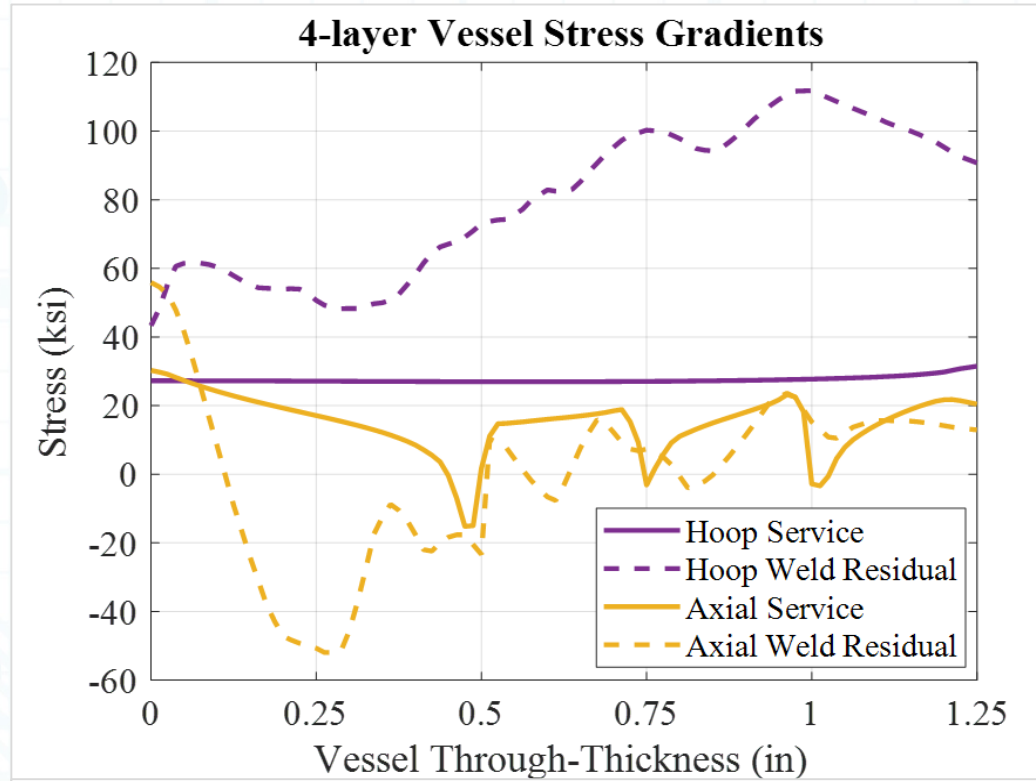
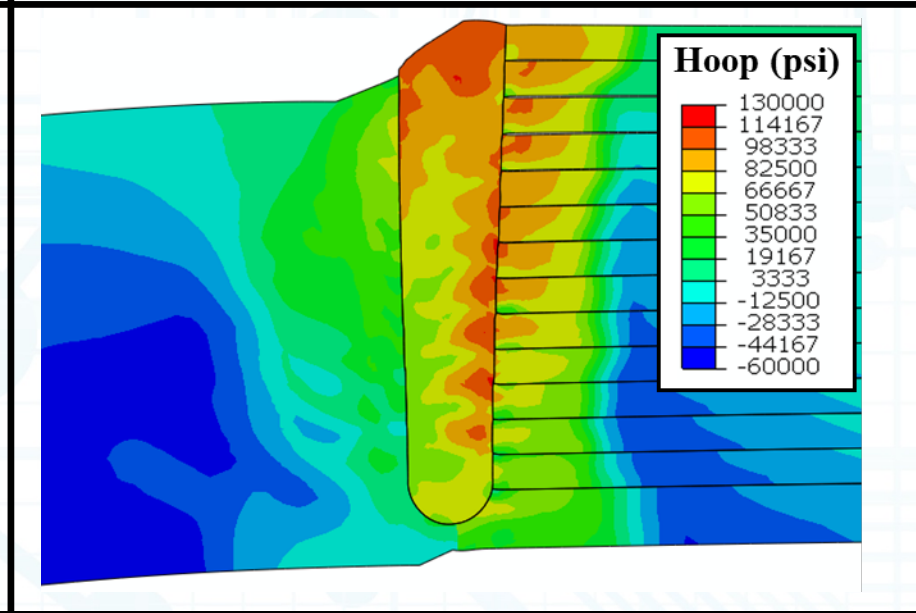
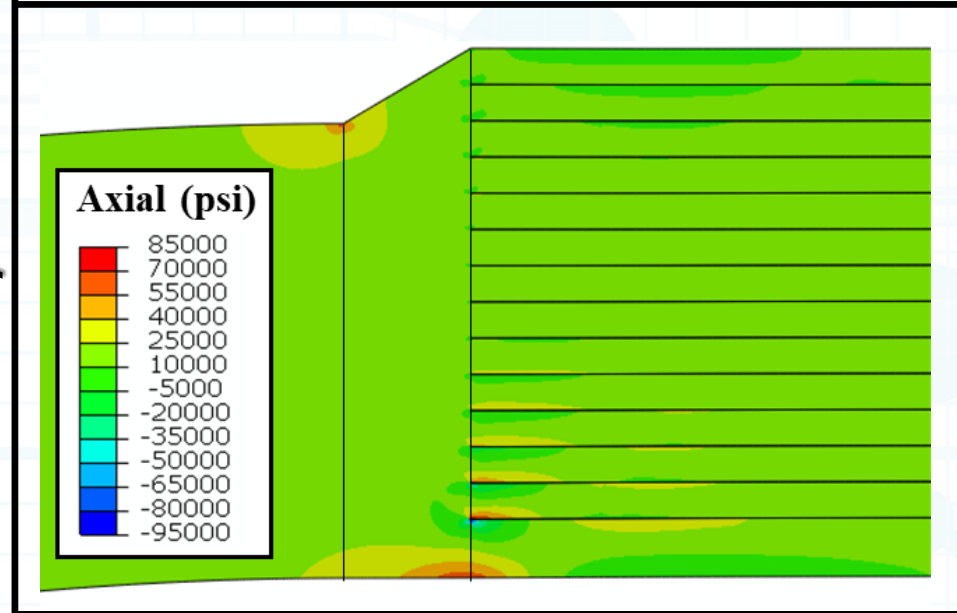
Axial Stress

Hoop Stress

4-Layer



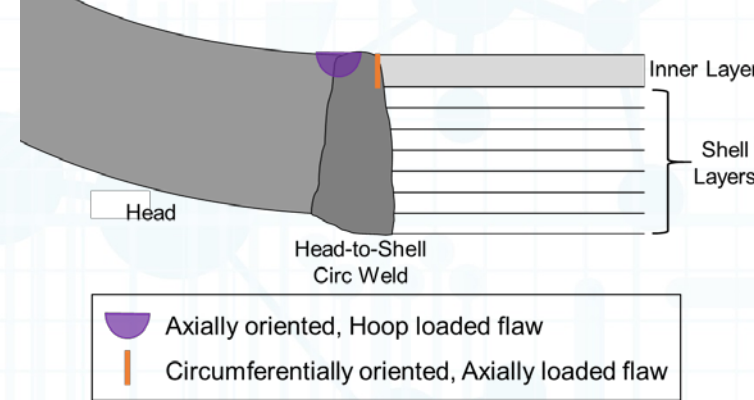
14-Layer



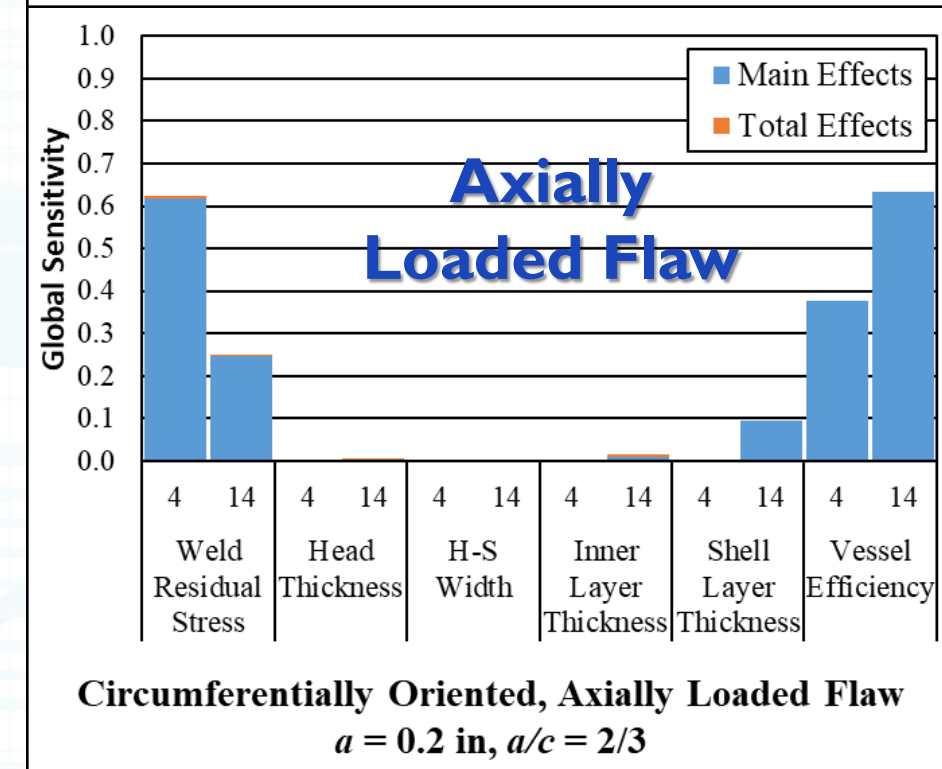
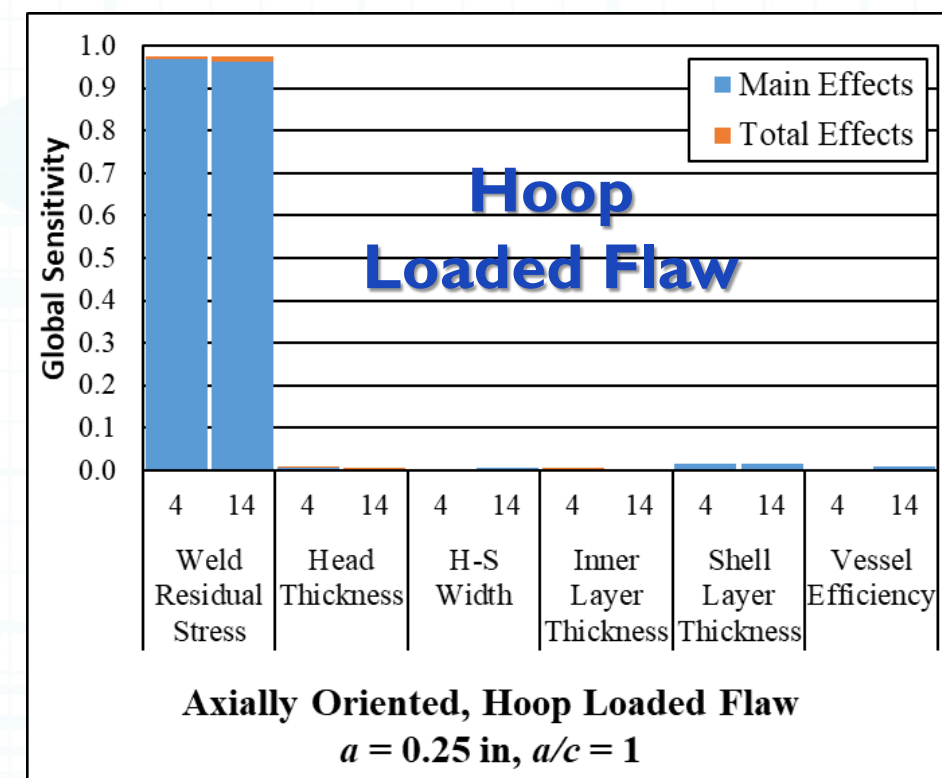
*Weld geometry differences have minimal effect on stress gradient predictions

*Stress predictions are more sensitive to gap size and through-thickness distribution

Sensitivity Studies



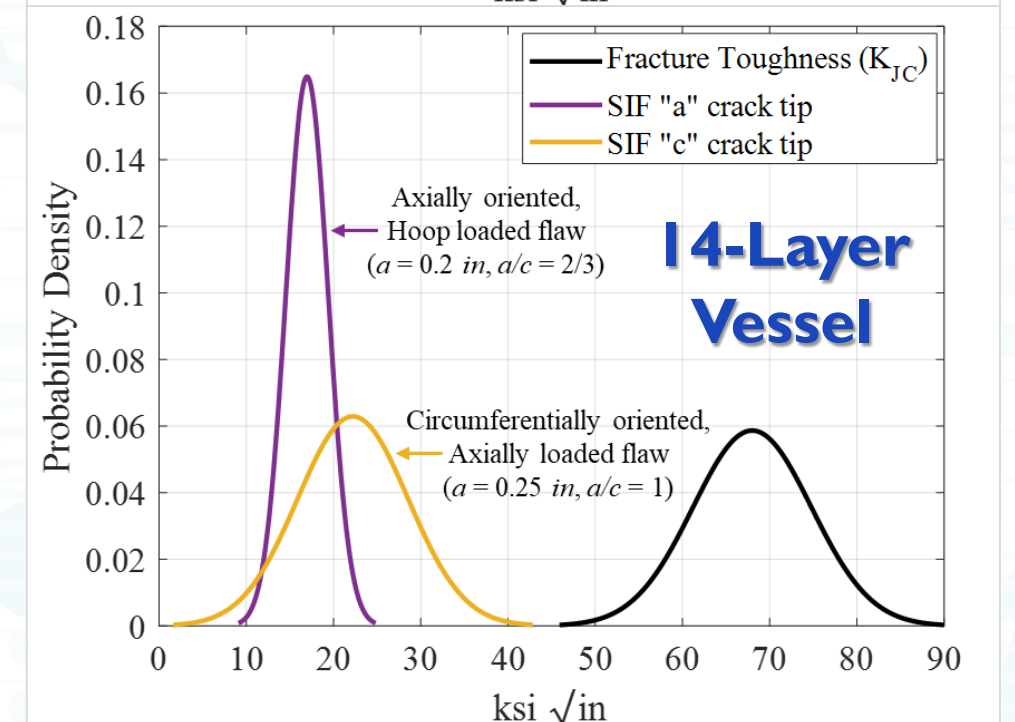
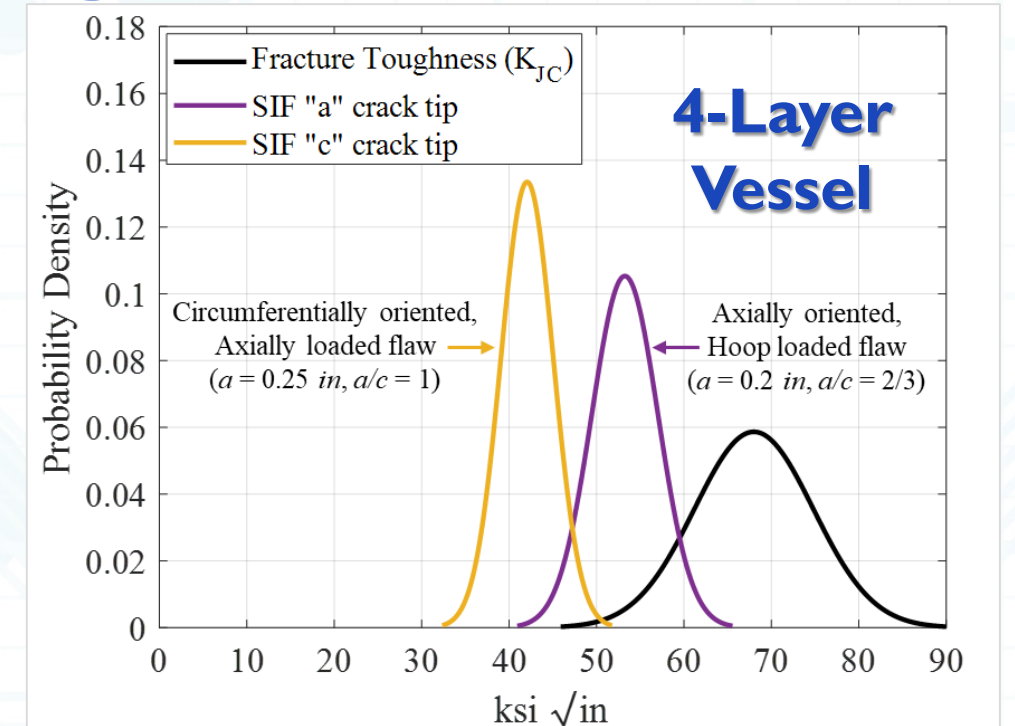
- Axially oriented, hoop loaded flaw:**
 - Variability in SIF is primarily the result of variation in WRS
- Circumferentially oriented, axially loaded flaw:**
 - Variability in SIF is primarily the result of variation in WRS and vessel efficiency → interlayer gaps
- Flaw size did not have a significant effect on sensitivity analysis
- Sensitivity analysis more dependent on flaw location
 - Flaw on shell-side is more sensitive to efficiency (interlayer gaps)
 - Relative influence of weld material properties is dependent on flaw location
- Thickness and weld width variation have minimal contribution to SIF variability



Stress Intensity Factor vs. Toughness

- NESSUS[®] used to generate CDF of $K_I \rightarrow$ converted to PDF to compare to K_{JC} in heat-affected zone
- Monte Carlo sampling used to perform integration:

$$p_f = \int_{g < 0} \dots \int f_X(x) dx$$
- **4-layer vessel**
 - “a” crack tip probability of $K_I > K_{JC} = 0.027$
 - “c” crack tip probability of $K_I > K_{JC} = 0.0002$
- **14-layer vessel**
 - Separation of K_I and K_{JC} PDFs: probability of $K_I > K_{JC} \approx 0$
- Predictions largely driven by uncertainty in WRS models/data and assumptions of fracture toughness variation



Conclusions

- Developed probabilistic framework to predict fracture risk in regions of interest
 - Includes models for WRS, service stress, SIF, and fracture toughness
 - Model development using V&V approach
 - Framework can utilize fatigue crack growth and failure assessment diagram capabilities in NASGRO®
- Probabilistic studies performed to predict variability in SIF and global sensitivities
 - Results are preliminary → used to demonstrate framework and guide resource allocation
 - WRS and vessel efficiency variation and uncertainty are largest drivers of SIF variability
 - Considerable variation and uncertainty in fracture toughness as well
- Further development and evaluation of this probabilistic framework are underway as one part of NASA's strategy to evaluate safety of LPV fleet

Acknowledgements

This work was conducted under funding from the NASA Headquarters Office of Safety and Mission Assurance (OSMA).

- Special Thanks to NASA Marshall Space Flight Center Personnel:
 - Brian Stoltz
 - Doug Wells
 - Joel Hobbs
 - Levi Shelton

Questions?

Backup Slides

4-layer Vessel Geometry and Loading/Boundary Condition (BC) Information

	Design	Distribution	Parameters
Geometry			
Head Thickness	1.056 ^c in	uniform ^d	a=1.056 b=1.1088
Diameter	24 in	deterministic	
Length ^a	118 in	deterministic	
Inner Layer Thickness	0.50 ^c in	uniform	a=0.50 b=0.54
Shell Layer Thickness	0.25 ^c in	uniform	a=0.25 b=0.29
Efficiency	≥ 50%	beta	$\alpha=7.8207$ $\beta=3.0674$ L=50 U=100
H-S Weld Width	0.875 in	uniform ^e	a=0.7437 b=1.0063
Loads/BCs			
Pressure ^b	3500 psi	deterministic	
Coefficient of Friction	0.7	deterministic	

^atangent-to-tangent vessel length

^bmaximum allowable working pressure (MAWP)

^cminimum

^dvariable range: -0, +5% from design

^evariable range: ±15% from design

$$E = 2.95 \times 10^7 \text{ psi}$$

$$\nu = 0.3$$

14-layer Vessel Geometry and Loading/Boundary Condition (BC) Information

	Design	Distribution	Parameters
Geometry			
Head Thickness	3.699 ^c in	uniform ^d	a=3.699 b=3.8840
Diameter	60.25 in	deterministic	
Length ^a	720 in	deterministic	
Inner Layer Thickness	0.46875 ^c in	uniform	a=0.46875 b=0.50875
Shell Layer Thickness	0.28125 ^c in	uniform	a=0.28125 b=0.32125
Efficiency	≥ 50%	beta	$\alpha=7.8207$ $\beta=3.0674$ L=50 U=100
H-S Weld Width	1.0625 in	uniform ^e	a=0.9031 b=1.2219
Loads/BCs			
Pressure ^b	5000 psi	deterministic	
Coefficient of Friction	0.7	deterministic	

^atangent-to-tangent vessel length

^bmaximum allowable working pressure (MAWP)

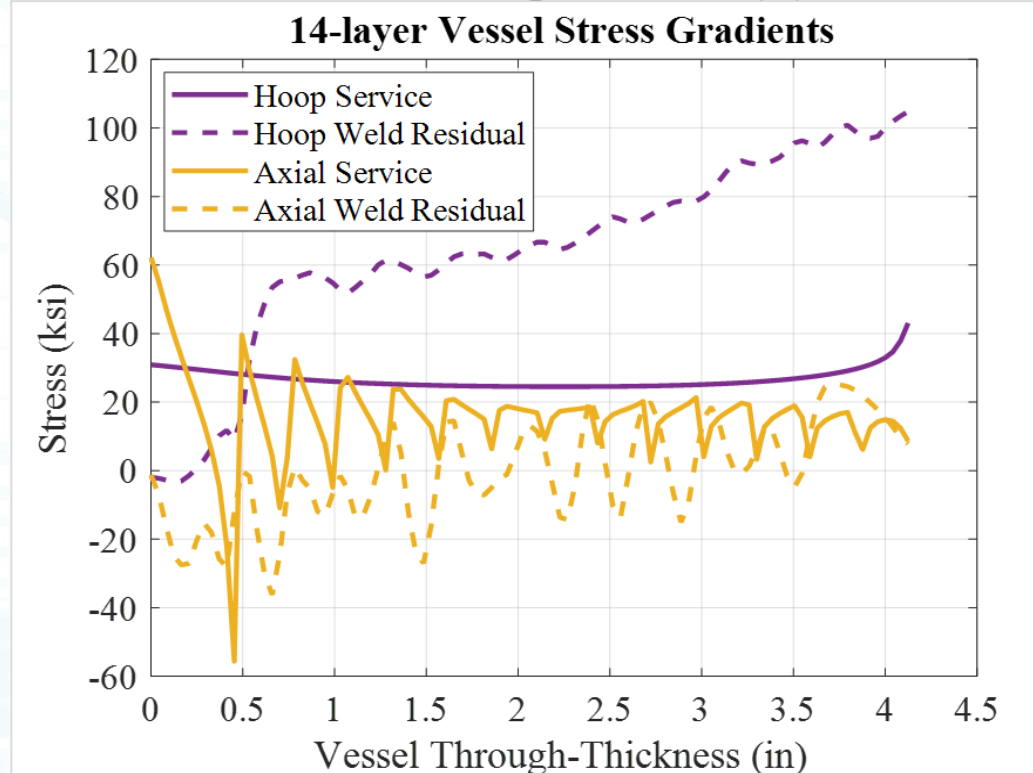
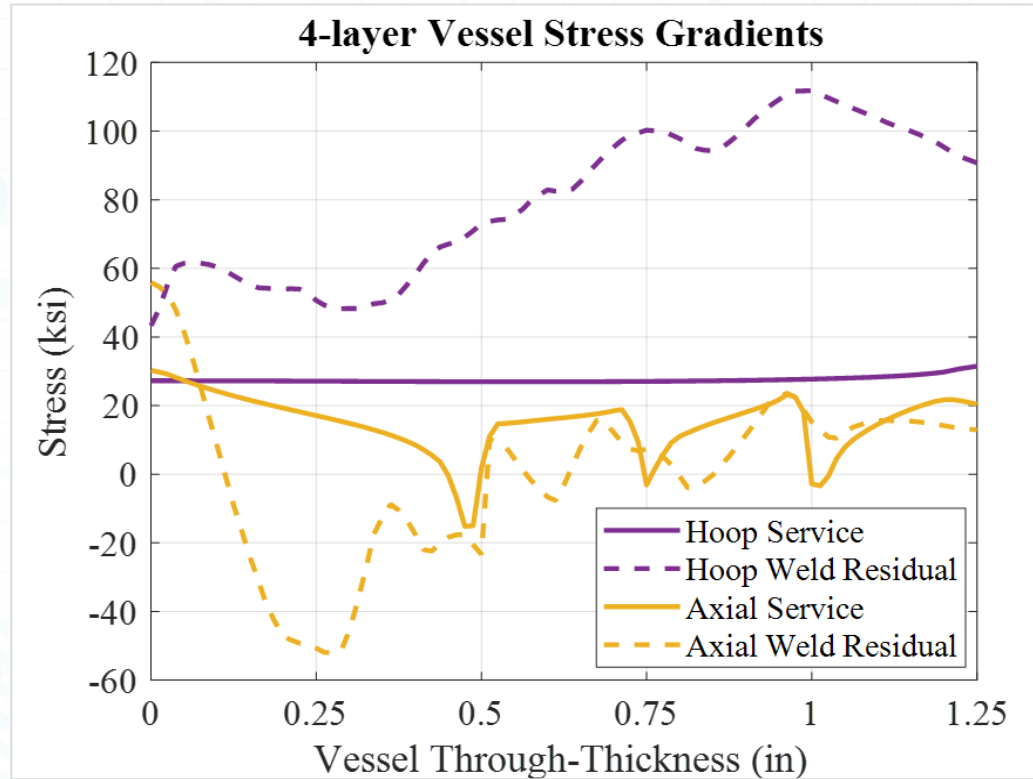
^cminimum

^dvariable range: -0, +5% from design

^evariable range: ±15% from design

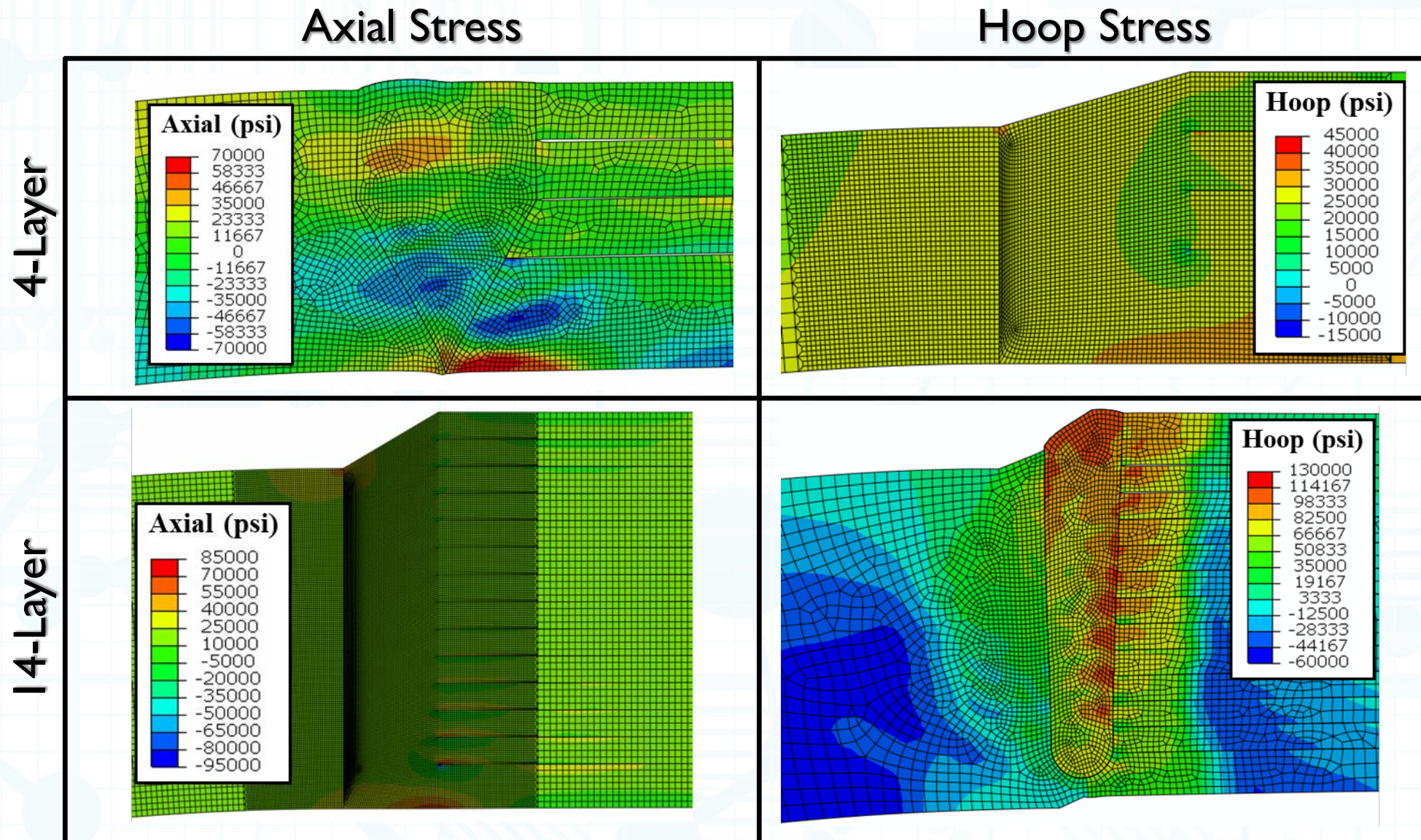
Surrogate Modeling Approach

- Principal component analysis (PCA) technique used to create surrogate model for service & WRS stress gradient
 - Predicts stress at multiple points (gradient) vs. single location
 - PCA reduces dimensionality of model output³
 - Greatly reduces computational time vs. FEA
- Surrogate Model Development Procedure:
 1. Run FE model based design of experiments to generate training data
 2. PCA used to express variation in gradients as linear combination of shape vectors → retaining only most important shape vectors reduces dimensionality
 3. Response surface to predict individual principal component score (eigenvalue) based on inputs → then reconstruct stress gradient as linear combination of most important shape vectors



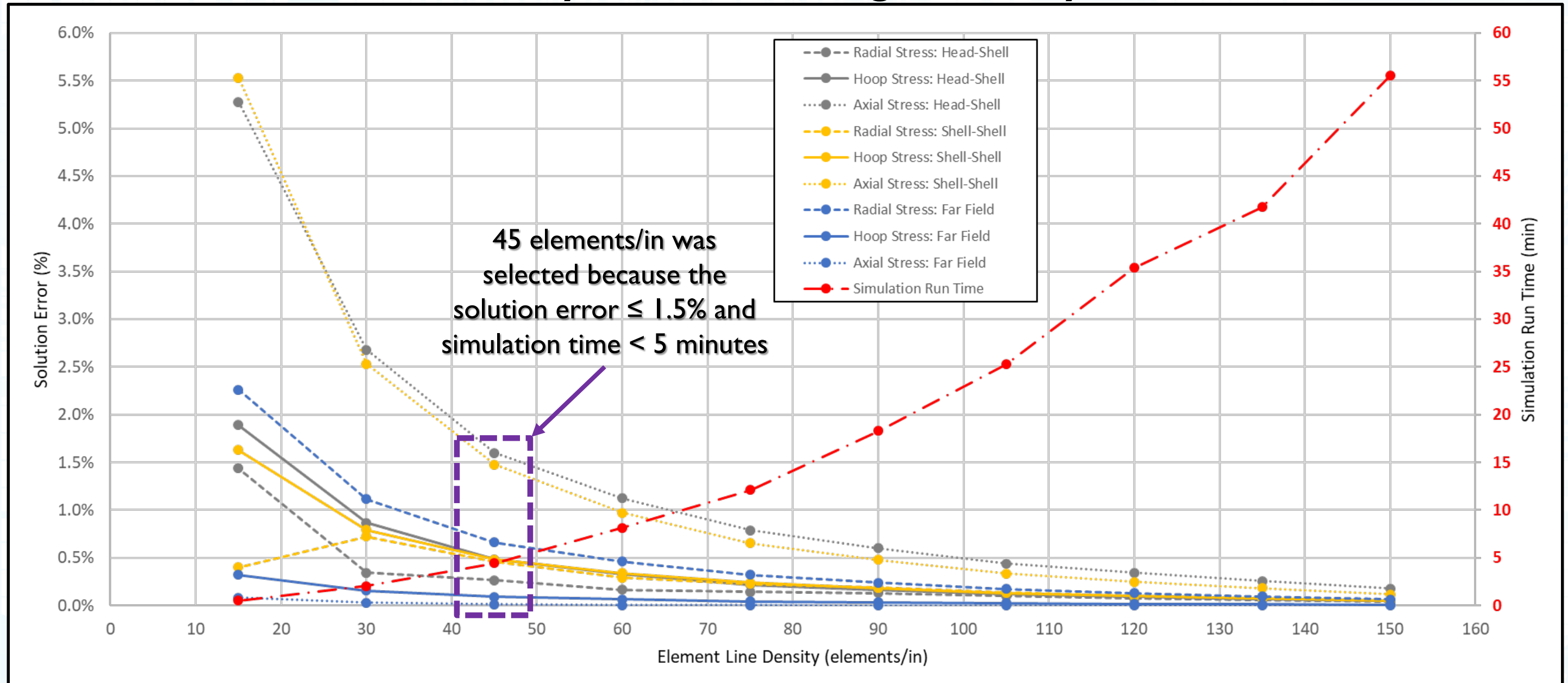
Nominal Contour Plots (with mesh shown)

- **Axial stress:**
 - Largest stress at inner surface
 - Gaps result in bending stress
- **Hoop stress:**
 - Largest stress at outer surface
 - Gaps result in stress concentrations
- Weld geometry differences have minimal effect on stress gradient predictions
- Stress predictions are more sensitive to interlayer gap size and through-thick distribution



Mesh Convergence

6-Layer Vessel Convergence Study



*Solution uses element line density of 200 elements/in

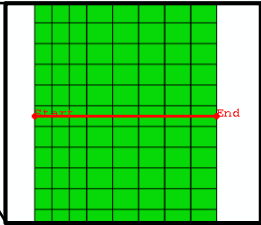
MECHANICAL ENGINEERING



Axisymmetric Model Verification

4-Layer Vessel

Far-Field Gradient



14-Layer Vessel

