Probabilistic Risk Assessment of Layered Pressure Vessels

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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: \( p_f = \int_{g<0} \ldots \int f_X(x)dx \)
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 \(\rightarrow\) cleavage toughness model
  - Uncertainty in cleavage transition to upper shelf \(\rightarrow\) use lower of cleavage or upper shelf toughness

\*Note: tables listing geometry and loading/boundary conditions for the 4- and 14-layer vessel are provided in backup slides
Probabilistic Framework
NESSUS Probabilistic Framework

Inputs:
- Service stress
- Weld residual stress
- Total thickness
- Initial crack depth ($a_0$)
- Initial crack shape ($a/c$)
- $da/dN$ model ($C, n$)

Outputs:
- Critical crack size
- Failure Assessment Diagram
- Critical Crack Size
- Probability of Detection

(A) NASSIF
- Gap sizes
- Service stress gradient

(B) NASGRO
- Inner layer mod.
- Shell layer mod.
- Head moduslus
- Circumference weld mod.

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

Risk Assessment

Vessel Efficiency and Basic Geometry

Gap Closure Tool

Gap Closure Tool

Sizes of Interlayer Gaps

Axisymmetric LPV Model

Service Stress Gradient in Weld

Weld Residual Stress Gradient

NASGRO

Toughness vs. SIF ($K_{IC} < K_I$)

Failure Assessment Diagram

Initial Flaw Size

Toughness ($K_{IC}$)

Critical Crack Size

Probability of Detection

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

### Inputs

<table>
<thead>
<tr>
<th>Vessel</th>
<th>d inner</th>
<th>t total</th>
<th># Layers</th>
<th>MAWP</th>
<th>MAWP 10%</th>
<th>Gap Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 in.</td>
<td>1.750</td>
<td>6</td>
<td>5500</td>
<td>5950</td>
<td>Gapping</td>
</tr>
</tbody>
</table>

### Outputs

- Through-thickness size of interlayer gaps and closure pressure
- Uses thin walled vessel theory and Excel’s Goal Seek function

Given a target efficiency, computes equivalent layer gapping

Calculates pressure-consistent stress history for all layers

### Table

<table>
<thead>
<tr>
<th>Layer #</th>
<th>T layer</th>
<th>Gap</th>
<th>R Layer</th>
<th>T closure</th>
<th>3D closure</th>
<th>R Mono</th>
<th>C closure</th>
<th>D closure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.5</td>
<td>0.000530</td>
<td>10.251</td>
<td>0.500</td>
<td>76.396</td>
<td>87.54</td>
<td>10.250</td>
<td>65.977</td>
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<td>1</td>
<td>0.25</td>
<td>0.000530</td>
<td>10.626</td>
<td>0.750</td>
<td>113.331</td>
<td>128.17</td>
<td>10.375</td>
<td>67.551</td>
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<tr>
<td>2</td>
<td>0.25</td>
<td>0.000530</td>
<td>10.877</td>
<td>1.000</td>
<td>149.476</td>
<td>166.85</td>
<td>10.500</td>
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<tr>
<td>3</td>
<td>0.25</td>
<td>0.000530</td>
<td>11.127</td>
<td>1.250</td>
<td>184.883</td>
<td>203.68</td>
<td>10.625</td>
<td>70.699</td>
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<td>4</td>
<td>0.25</td>
<td>0.000530</td>
<td>11.378</td>
<td>1.500</td>
<td>219.602</td>
<td>238.76</td>
<td>10.750</td>
<td>72.273</td>
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<tr>
<td>5</td>
<td>0.25</td>
<td>0.009103</td>
<td>11.637</td>
<td>1.750</td>
<td>437.813</td>
<td>467.05</td>
<td>10.875</td>
<td>73.901</td>
</tr>
<tr>
<td>6</td>
<td>0.25</td>
<td>0.000000</td>
<td>11.762</td>
<td>1.750</td>
<td>0.000</td>
<td>0.000</td>
<td>10.875</td>
<td>73.901</td>
</tr>
<tr>
<td>31</td>
<td>0.25</td>
<td>0.000000</td>
<td>11.762</td>
<td>1.750</td>
<td>0.000</td>
<td>0.000</td>
<td>10.875</td>
<td>73.901</td>
</tr>
<tr>
<td>Proof</td>
<td>0.25</td>
<td>0.005355</td>
<td>11.767</td>
<td>1.750</td>
<td>2581.881</td>
<td>2750.00</td>
<td>10.875</td>
<td>73.935</td>
</tr>
</tbody>
</table>

### Adjustments

- **Multiplier:**
  - # Gapping Type
  - 1: uniform
  - 2: linear change through thickness
  - 3: inner only (most conservative for inner layer)
  - 4: linear change through thickness

- **Gap Distribution:**
  - 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 $\rightarrow$ elastic-plastic WRS field prediction
  - Include hydro test at 1.5 times max pressure in simulation $\rightarrow$ 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 software 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
Preliminary Results

Reference Flaw Sizes

- $a = 0.25 \text{ in}, a/c = 1$
- $a = 0.2 \text{ in}, a/c = 2/3$
*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 $K_I$ → converted to PDF to compare to $K_{JC}$ in heat-affected zone
- Monte Carlo sampling used to perform integration:
  $$p_f = \int_{g<0} \ldots \int f_X(x)\,dx$$
- 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

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Design</th>
<th>Distribution</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head Thickness</td>
<td>1.056c</td>
<td>uniformd</td>
<td>a=1.056 b=1.1088</td>
</tr>
<tr>
<td>Diameter</td>
<td>24 in</td>
<td>deterministic</td>
<td></td>
</tr>
<tr>
<td>Lengtha</td>
<td>118 in</td>
<td>deterministic</td>
<td></td>
</tr>
<tr>
<td>Inner Layer Thickness</td>
<td>0.50c</td>
<td>uniform</td>
<td>a=0.50 b=0.54</td>
</tr>
<tr>
<td>Shell Layer Thickness</td>
<td>0.25c</td>
<td>uniform</td>
<td>a=0.25 b=0.29</td>
</tr>
<tr>
<td>Efficiency</td>
<td>≥ 50%</td>
<td>beta</td>
<td>α=7.8207 β=3.0674 L=50 U=100</td>
</tr>
<tr>
<td>H-S Weld Width</td>
<td>0.875 in</td>
<td>uniformc</td>
<td>a=0.7437 b=1.0063</td>
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<tr>
<td><strong>Loads/BCs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressureb</td>
<td>3500 psi</td>
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<tr>
<td>Coefficient of Friction</td>
<td>0.7</td>
<td>deterministic</td>
<td></td>
</tr>
</tbody>
</table>

| 14-layer Vessel Geometry and Loading/Boundary Condition (BC) Information |
|-------------------|---------|--------------|--------------------------|
| Geometry          | Design  | Distribution | Parameters               |
| Head Thickness    | 3.699c  | uniformd     | a=3.699 b=3.8840         |
| Diameter          | 60.25 in| deterministic|                          |
| Lengtha           | 720 in  | deterministic|                          |
| Inner Layer Thickness | 0.46875c | uniform | a=0.46875 b=0.50875 |
| Shell Layer Thickness | 0.28125c | uniform | a=0.28125 b=0.32125 |
| Efficiency        | ≥ 50%   | beta         | α=7.8207 β=3.0674 L=50 U=100 |
| H-S Weld Width    | 1.0625 in| uniformc     | a=0.9031 b=1.2219        |
| **Loads/BCs**     |         |              |                          |
| Pressureb         | 5000 psi| deterministic|                          |
| Coefficient of Friction | 0.7     | deterministic|                          |

\[ E = 2.95 \times 10^7 \text{ psi} \quad \nu = 0.3 \]

\( ^a \text{tangent-to-tangent vessel length} \)
\( ^b \text{maximum allowable working pressure (MAWP)} \)
\( ^c \text{minimum} \)
\( ^d \text{variable range: -0, +5% from design} \)
\( ^e \text{variable range: ±15% from design} \)
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 output\(^3\)
  - 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

45 elements/in was selected because the solution error ≤ 1.5% and simulation time < 5 minutes

*Solution uses element line density of 200 elements/in
Axisymmetric Model Verification

4-Layer Vessel

Far-Field Gradient

14-Layer Vessel