VVS2015-8015: Comparing Closed-Form Solutions to Computational Methods for Predicting and Validating Stresses at Nozzle-to-Shell Junctions on Pressure Vessels Subjected to Piping Loads

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Introduction

- Often times, piping loads acting on nozzles need to be considered when designing pressure vessels.
- Quantifying stresses at nozzle-to-shell junctions on equipment subjected to supplemental piping loads is essential when designing pressure retaining components in the petrochemical, chemical, and nuclear industries.
- Accurately and efficiently predicting and validating the stress state at nozzle-to-shell junctions is an important aspect of understanding the propensity for failure from plastic collapse and the potential for initiation of crack-like flaws, which could lead to brittle fracture.
- The intent of this study is to highlight multiple simplified methods for determining the elastic stresses at nozzle-to-shell junctions due to internal pressure and external piping loads and to compare results to understand the advantages and limitations of each methodology.
Welding Research Council (WRC) Bulletin 107 provides methods for calculating local stresses in spherical and cylindrical shells due to external loading.

WRC Bulletin 297 broadens and expands upon the methodologies of WRC Bulletin 107; a wider range of vessel geometries (diameter to thickness ratios) are included.

The more recent WRC Bulletin 537 facilitates more efficient and accurate implementation of WRC Bulletin 107 through precise equations and data fitting techniques.

These closed-form solutions for estimating local stresses at nozzle-to-shell junctions are discussed in this study and compared to multiple computational techniques, including the use of several commercially available FEA-based software tools.

Both 3D shell and solid finite element modeling techniques are employed and compared. In particular, nozzles subjected to internal pressure, axial forces, and bending moments are analyzed.

Modeling simplifications such as not modeling fillet welds and tying re-pads directly to the shell are discussed.
Objectives

- The comparisons presented in this study offer insight into the range of analysis techniques available to the user when designing a component to withstand supplemental piping loads.
  - Furthermore, detailed FEA results validate and provide some perspective on the most practical analysis approach for a given design application.
- In this presentation, solid and shell finite element models (constructed using the commercial FEA software, Abaqus) are benchmarked against NozzlePro, FAST2, and WRC Bulletin 297 calculations for different nozzle geometries.
  - The effects of including welds and treatment of the re-pad in the FEA model are investigated.
  - Results for internal pressure, nozzle axial forces, torsional moments, and bending moments are compared.
  - Stress components from simplified shell-based FEA programs are validated based on comparison to detailed finite element models.
  - Calculated stresses from WRC 297 are also compared to the detailed finite element models.
  - The assumptions associated with simplified methods are quantified.
NozzlePro Background

- NozzlePro is a shell element based nozzle analysis program designed to efficiently analyze nozzle-to-shell junctions.
  - Capable of analyzing nozzles with reinforcing pads, offset in translation and tilt angle, and attempts to account for fillet welds.
  - Geometries supported are nozzles going into cylindrical shells, and hemispherical, elliptical, dished, conical, and flat heads.
  - Contains a 3D viewer capable of displaying displacement results and stress contours.
  - Code compliance based on ASME Section VIII Division 2.
- NozzlePro provides a list of stress intensities at different locations in the nozzle and vessel.
- Individual stress components are not provided.
- Stresses at multiple locations in the vessel and nozzle moving away from the junction are not provided.
- Based on comparisons performed in this study, NozzlePro seems to be under-conservative when the weld is included in the model.
NozzlePro User Interface

Note these inputs are described in the images below.
FAST2 Background

- The development of FAST2 was motivated by the inadequacies of WRC 107 that is based on the calculation procedures developed by Bijlaard for cylindrical and spherical vessels.
  - For the cylindrical shell nozzle intersection, Bijlaard assumed that the nozzle acted as a rigid insert; therefore, stress results can only be obtained in the shell.
  - This assumption can be non-conservative (especially for nozzle loads) in that the maximum stress typically occurs in the nozzle neck rather than the shell if the nozzle neck is thinner than the shell.
  - To overcome these inadequacies, WRC 297 has been prepared based on the analytical procedures contained in FAST2 (thin shell theory methods by C.R. Steel).
  - FAST2 includes the capability for analyzing a finite length of nozzle and pad reinforcing of the vessel which is not obtainable from WRC 107 or WRC 297.
  - Substantial savings in material and reliability can be gained from the accurate analysis of the actual configuration.

- Stress analysis results can be obtained at a number of locations on the vessel, on the nozzle, and around the intersection with the FAST2 Module. WRC 297 only allows stresses to be obtained at four points.
Stress Comparisons

- Stresses are compared at multiple locations for a nozzle intersecting a cylinder with a reinforcing pad and a nozzle into an elliptical head (with and without the fillet weld).
  - \( t/2 \) in the nozzle and vessel
  - \( t/2 + w \) in the nozzle and vessel

- Stresses are typically extracted at \( t/2 \) away from the junction in shell models because of the singularity (sharp corner) associated with the nozzle-to-shell junction geometry.
Nozzle into Elliptical Head

- Stress linearization locations shown for solid FEA model with/without weld
Stress Attenuation Comparisons

Nozzle Hoop Stress on Outer Surface (Pressure only)

- Blue circle: Abaqus solid model with weld
- Red square: FAST2
- Green triangle: Abaqus solid model without weld
- Purple diamond: Abaqus shell model

Graph showing the hoop stress on the outer surface of a nozzle as a function of distance along the nozzle in inches. The stress values are measured in pounds per square inch (psi).

Distance along nozzle (in):
-0.105 to 2.895

Hoop stress on outer surface (psi):
- 18,000 to 0
Pressure Loading at Junction

- Pressure Loading at Junction Location (Pressure only loadcase)

- Average Tresca membrane stress (psi)

- Model and location:
  - Abaqus solid model without weld (t/2)
  - Abaqus shell model junction
  - Abaqus shell model (t/2)
  - NozzlePro without weld (t/2)
  - FAST2 (t/2)

- Comparison between Nozzle Next to Shell and Shell Next to Nozzle.
Pressure Loading at Fillet Weld

![Chart showing pressure loading at fillet weld with different models and locations.](chart.png)
Bending Moment Loading

**Graph:**
- **Title:** t/2+w and Location (Nozzle bending moment only loadcase)
- **Y-axis:** Average Tresca membrane stress (psi)
- **X-axis:** Model and location

- **Legend:**
  - Nozzle Next to Shell
  - Shell Next to Nozzle

**Models and Locations:**
- Abaqus solid model with weld (t/2+w)
- Abaqus solid model without weld (t/2+w)
- Abaqus shell model (t/2+w)
- NozzlePro with weld (t/2+w)
- *FAST2 (t/2+w)
Nozzle with Re-Pad into Cylinder

- 3D solid FEA model shown and stress linearization locations are highlighted.

- Comparisons are made with contact defined between the re-pad and the shell and with it tied directly to the shell (integrally connected).
Stress Attenuation Comparisons

Nozzle Hoop Stress on Inner Surface (Pressure only)

- Abaqus solid model with welds (contact)
- FAST2
- Abaqus solid model with welds (tie)
Axial Force Loading

Stress Intensity Comparisons (Nozzle axial force loadcase)

- Pad/Header Junction
- Pad Outer Edge Weld
- Header Outside Pad Area
- Branch at Junction
- Branch Removed from Junction

Model:
- Abaqus solid model
- NozzlePro without welds
- NozzlePro with welds
- FAST2

Average Tresca membrane stress (psi)
Torsional Moment Loading

Stress Intensity Comparisons (Nozzle torsional moment loadcase)

- Pad/Header Junction
- Pad Outer Edge Weld
- Header Outside Pad Area
- Branch at Junction
- Branch Removed from Junction

Average Tresca membrane stress (psi)

Model

- Abaqus solid model
- NozzlePro without welds
- NozzlePro with welds
- FAST2
Internal Pressure Loading

Stress Intensity Comparisons (Nozzle bending moment loadcase)

- Pad/Header Junction
- Pad Outer Edge Weld
- Header Outside Pad Area
- Branch at Junction
- Branch Removed from Junction

Average Tresca membrane stress (psi)

Model:
- Abaqus solid model
- NozzlePro without welds
- NozzlePro with welds
- FAST2

Graph showing comparisons of stress intensity for different models and configurations.
WRC 107/537 Summary

- WRC Bulletin 107 was originally published in 1965 and is based on the work of Prof. Bijlaard.
  - Extended Bijlaard’s original work using test data and has been widely used as an analytical tool over the years.
  - This approach is well suited for considering stresses in shells at lug attachments (round or square lug considered to be rigid). Adjustments can be made for hollow attachments such as nozzles.
  - Provides stresses in spherical and cylindrical shells, but not in the attachment or nozzle itself.
- WRC Bulletin 537 facilitates more efficient and accurate implementation of WRC Bulletin 107 through precise equations and data fitting techniques.
- Again, calculation of stresses in the nozzle is not included in the methodology.
WRC 297 Methodology

- WRC Bulletin 297 presents a formulation to calculate stress components at the nozzle-vessel junction.
  - Intended for nozzles radially intersecting cylinders.
- This bulletin broadens the coverage of WRC Bulletin 107 and is based on thin shell theory (C.R. Steele).
- Nozzle axial forces and moments in the transverse and longitudinal planes are compared to shell finite element models.
- Stresses in the vessel and nozzle can be calculated.
- Methodology not intended to cover nozzles with hillside offset. Additionally, nozzles intersecting heads not formally addressed.
- Estimation of stress in nozzle neck can be critical (location can limit).
Vessel Stresses:

\[
\sigma_r = \frac{P}{T^2} (n_r \pm 6m_r),
\]

\[
\sigma_\theta = \frac{P}{T^2} (n_\theta \pm 6m_\theta),
\]

\[
\sigma_r = \frac{M_i}{T^2d} (n_r \pm 6m_r),
\]

\[
\sigma_\theta = \frac{M_i}{T^2d} (n_\theta \pm 6m_\theta).
\]

Nozzle Stresses:

\[
\sigma_c = \frac{P}{T^2} (n_\theta)
\]

\[
\sigma_a = \frac{P}{t^2} \left[ \frac{t}{\pi d} \pm (6m_r - 3n_r) \right],
\]

\[
\sigma_a = \frac{M_i}{t^2d} \left[ \frac{4t}{\pi d} \pm (6m_r - 3n_r) \right].
\]
WRC 297 Stress Comparisons

- Four geometries from Appendix B of WRC 297 are modeled using shell elements and compared to the WRC 297 calculations (directly at the junction).
- The four geometries are given below:

<table>
<thead>
<tr>
<th>Model</th>
<th>Nozzle Diameter (d)</th>
<th>Nozzle Thickness (t)</th>
<th>Vessel Diameter (D)</th>
<th>Vessel Thickness (T)</th>
<th>$\lambda [(d/D)(D/T)^{1/2}]$</th>
<th>d/t</th>
<th>T/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>WRC-A</td>
<td>10</td>
<td>0.2</td>
<td>400</td>
<td>1</td>
<td>0.5</td>
<td>50</td>
<td>5</td>
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<tr>
<td>WRC-B</td>
<td>10</td>
<td>0.2</td>
<td>1000</td>
<td>0.4</td>
<td>0.5</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>WRC-C</td>
<td>10</td>
<td>0.2</td>
<td>2000</td>
<td>0.2</td>
<td>0.5</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>WRC-D</td>
<td>10</td>
<td>0.2</td>
<td>4000</td>
<td>0.1</td>
<td>0.5</td>
<td>50</td>
<td>0.5</td>
</tr>
</tbody>
</table>

- These geometries offer a range of D/T and T/t ratios to help validate the applicability of the closed-form solutions and investigate the robustness of the general methodology.
In general, there is good agreement with the exception of membrane + bending stress in the hoop direction for the nozzle. This is because the WRC 297 formulation neglects circumferential bending stress in the nozzle at the nozzle-to-shell junction.

<table>
<thead>
<tr>
<th>Maximum Membrane Stress (psi)</th>
<th>WRC 297 B</th>
<th>Abaqus Shell Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>WRC 297 Calculation</td>
<td></td>
</tr>
<tr>
<td>Loadcase</td>
<td>P</td>
<td>M_C</td>
</tr>
<tr>
<td>Vessel hoop stress</td>
<td>1713</td>
<td>69</td>
</tr>
<tr>
<td>Vessel longitudinal stress</td>
<td>1713</td>
<td>69</td>
</tr>
<tr>
<td>Nozzle hoop stress</td>
<td>1713</td>
<td>-55</td>
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<tr>
<td>Nozzle longitudinal stress</td>
<td>156</td>
<td>61</td>
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<td>Vessel stress intensity</td>
<td>1713</td>
<td>123</td>
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<tr>
<td>Nozzle stress intensity</td>
<td>1713</td>
<td>116</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Maximum Membrane + Bending Stress (Outer Surface) (psi)</th>
<th>WRC 297 B</th>
<th>Abaqus Shell Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>WRC 297 Calculation</td>
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</tr>
<tr>
<td>Loadcase</td>
<td>P</td>
<td>M_C</td>
</tr>
<tr>
<td>Vessel hoop stress</td>
<td>8913</td>
<td>1590</td>
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<td>Vessel longitudinal stress</td>
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<tr>
<td>Nozzle hoop stress</td>
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<td>Nozzle longitudinal stress</td>
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<tr>
<td>Vessel stress intensity</td>
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<td>Nozzle stress intensity</td>
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<td>2946</td>
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</table>
Conclusions

- This presentation summarizes aspects of a comprehensive validation effort to compare simplified approaches to rigorous FEA.
- In general, all of the methodologies compared herein are in reasonable agreement.
  - NozzlePro stress intensities are in good agreement with 3D shell and solid finite element models in addition to FAST2.
- Primary membrane stresses for the pressure only loadcases are in agreement with the calculations in Section VIII Division 2, Part 4.
- NozzlePro tends to be under-conservative with the inclusion of welds, but generally agrees with 3D FEA results.
- Component stresses from FAST2 (moving away from the junction) match 3D FEA models very well (making it a useful tool for efficiently evaluating stress attenuation).
- In general, stresses at the nozzle-to-shell junction from WRC 297 are in agreement with 3D, solid finite element models.
  - The exception is for circumferential nozzle bending stress (WRC 297 neglects this stress component). Thus, WRC 297 can be under conservative for predicting hoop stresses in the nozzle.
  - Additionally, significant portions of the WRC 297 plots contain regions that fall outside the bounds of reasonable geometries.
Conclusions (Continued)

- Neglecting the fillet weld from a 3D FEA model and linearizing stress at the junction is generally conservative (vs. explicitly modeling the fillet weld).
- Tying the entire re-pad to the shell (integrally connected), is a reasonable modeling assumption and eliminates the complexity of using contact, etc.
- Simplified programs such as NozzlePro/FAST2 are useful as long as the limitations and general accuracy are understood.
  - Simple programs are efficient and practical to use to get a sense of elastic stress magnitudes at nozzle-to-shell junctions.
  - They don’t always offer the entire picture (i.e. limited amount of stress output: lack of stress components, limited data moving away from the junction, etc.)
  - Can be under-conservative for some load cases or when fillet welds are included in the analysis.
- Closed form solutions from WRC Bulletin 297/537 are very convenient to implement but also have limitations.
- If practical, 3D solid FEA with stress linearization is the most rigorous approach to estimate stresses at nozzle-to-shell junctions. This would be recommended for critical applications.