Spot-Weld Fatigue Optimization

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PROJECT OBJECTIVES

- Identify suitable spot-weld modelling technique.
- Identify method to predict spot-weld fatigue life.
- Evaluate different optimization methods.
- Formulate recommendation.
Resistance spot welding – RSW.

Stress Concentrations “hot spots”.

Hard to model due to,

- Material behavior.
- Residual stresses.
- Complex geometry.
RESEARCH PROCESS

- Identify and compare modeling techniques.
- Identify and compare different fatigue estimation methods.
- Investigate modeling techniques and fatigue estimation methods compatibility with optimization.
- Set up optimization problem formulation including design variables, responses, constraints and objectives – DRCO.
- Select solver methods and algorithms.
- Compare results.
- Real life applications.
FATIGUE ESTIMATION METHODS

- High cycle fatigue – HCF.
- Low cycle fatigue – LCF.
- Stress based damage \( N \geq 10^4 \).
- Strain based damage \( N \leq 10^4 \).
- Constant amplitude – CA loading.
- Variable amplitude – VA loading.
- Palmgren-Miner,
  \[
  D = \sum_{i=1}^{k} \frac{n_i}{N_i}
  \]
- Rain-flow counting.
RUPP’S STRUCTURAL STRESS

- Detailed stress FE-analysis not practical
- Analytical approach of formulating stress around spot-welds
- Based on beam and annular plate theory
RUPP’S STRUCTURAL STRESS

Failure mode: Sheets

\[ \sigma_r(\theta) = -\sigma(F_x) \cos \theta - \sigma(F_y) \sin \theta + \sigma(F_z) + \sigma(M_x) \sin \theta - \sigma(M_y) \cos \theta \]

\[ \sigma(F_{x,y}) = \frac{F_{x,y}}{\pi dt} \]

\[ \sigma(F_{z}) = \kappa\left(\frac{1.744F_{z}}{t^2}\right) \text{ for } F_z > 0 \]

\[ \sigma(F_{z}) = 0 \text{ for } F_z \leq 0 \]

\[ \sigma(M_{x,y}) = \kappa\left(\frac{1.872M_{x,y}}{dt^2}\right) \]

\[ \kappa = 0.6\sqrt{t} \]
RUPP’S STRUCTURAL STRESS

Failure mode: Nugget

\[
\tau(\theta) = \tau_{\text{max}}(F_x) \cos \theta + \tau_{\text{max}}(F_y) \cos \theta
\]

\[
\sigma(\theta) = \sigma(F_z) + \sigma_{\text{max}}(M_x) \sin \theta - \sigma_{\text{max}}(M_y) \cos \theta
\]

\[
\tau_{\text{max}}(F_{x,y}) = \frac{16F_{x,y}}{3\pi d^2}
\]

\[
\sigma(F_z) = \frac{4F_z}{\pi d^2} \quad \text{for} \quad F_z > 0
\]

\[
\sigma(F_z) = 0 \quad \text{for} \quad F_z \leq 0
\]

\[
\sigma(M_{x,y}) = \frac{32M_{x,y}}{\pi d^3}
\]
RUPP’S STRUCTURAL STRESS

- From FE forces local effective stresses computed analytically.
- Three effective stresses evaluated, top sheet/bottom sheet and nugget.
- Cycles identified and calculated using rain-flow counting.
- Palmgren-Miner and SN data used to evaluate accumulated damage.
- Rupp’s correctional factor,

\[ S_0 = \frac{S + M_s S_m}{M_s + 1} \]
SPOT-WELD MODELING

- Point to point – PTP connector
  - Rod, Bar, Beam, Bush
  - Node/node

- CWELD connector
  - Timoshenko beam
  - Node/node node/patch patch/patch

- Area contact method – ACM connector
  - Solid element
  - Interpolation elements (RBE3)
Benchmark structures that is recurring in similar studies.

- Tensile shear specimen – TS specimen.

- Coach peel specimen – CP specimen.

- Structures replication of specimen used by Xin Long, Sanjeev K. Khanna
Fatigue life evaluated using,
• Nominal stress approach.
• Local structural stress approach.

Spot-weld modeled with,
• Beam.
• CWELD.
• ACM 1 Hexa.
• ACM 4 Hexa.
One dimensional unit line load applied.

- Sinusoidal load.
- Load ratio $R = 0.1$.
- Load scaled in fatigue tool to match experimental data.

- Sheets modeled with first order quadrilateral shell elements.
- Material from Xin Long, Sanjeev K. Khanna and Ncode material Library.
- Experimental data.
- High strength low alloy - HSLA steel
SINGLE WELD BENCHMARK

BENCHMARK RESULTS

- Extraction of forces in weld elements and verification of Rupp's equations.
- Evaluated fatigue life results using Rupp's structural stress approach.
SINGLE WELD BENCHMARK

BENCHMARK RESULTS – TS SPECIMEN

TENSILE SHEAR, Element Size 1 mm

Test Data
- ACM, 4hexa, Shell
- ACM, 4hexa, SPW
- ACM, 1hexa, Shell
- ACM, 1hexa, SPW
- BEAM, SPW
- CWELD, SPW

TENSILE SHEAR, Element Size 2 mm

Test Data
- ACM, 4hexa, Shell
- ACM, 4hexa, SPW
- ACM, 1hexa, Shell
- ACM, 1hexa, SPW
- BEAM, SPW
- CWELD, SPW

TENSILE SHEAR, Element Size 4 mm

Test Data
- ACM, 4hexa, Shell
- ACM, 4hexa, SPW
- ACM, 1hexa, Shell
- ACM, 1hexa, SPW
- BEAM, SPW
- CWELD, SPW

Over-all mesh dependency

ACM, 1mm
ACM, 2mm
ACM, 4mm
ACM4.1mm
ACM4.2mm
ACM4.4mm
CWEELD, 1mm
CWEELD, 2mm
CWEELD, 4mm
BEAM, 1mm
BEAM2mm
BEAM4mm
minimize \quad S(x)
\quad \forall x \in \mathbb{R}^m
subject to \quad -A(x) \leq -A_{\text{constraint}} \quad (\ast)
\quad x_e \leq x_e \leq \overline{x}_e, \quad e = 1, \ldots, m.
Geometry originating from study conducted by Ann-Britt Ryberg.

- 56 welds candidates for reduction.
- Symmetric sheet metal tube with one longitudinal center plate.
- Both two and three layer welds.
Torsion load.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Nominal</th>
<th>Optimization Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Spot-Welds, $n$</td>
<td>56</td>
<td>Minimize</td>
</tr>
<tr>
<td>Fatigue Life, $L$</td>
<td>7 040 000</td>
<td>≥ 6200000</td>
</tr>
<tr>
<td>Torsional stiffness, $C_t$, [Nm/deg]</td>
<td>43.84</td>
<td>≥ 41.65</td>
</tr>
<tr>
<td>Bending stiffness &quot;rocker&quot;, $C_{br}$, [N/mm]</td>
<td>25 740</td>
<td>≥ 24450</td>
</tr>
<tr>
<td>Bending stiffness &quot;tunnel&quot;, $C_{bt}$, [N/mm]</td>
<td>342.0</td>
<td>≥ 324.9</td>
</tr>
<tr>
<td>First torsional mode (= mode 2), $F_{m2}$, [Hz]</td>
<td>44.61</td>
<td>≥ 42.38</td>
</tr>
<tr>
<td>Average beam length after crash, $d$, [mm]</td>
<td>391.1</td>
<td>≥ 380</td>
</tr>
</tbody>
</table>

Bending load.
Design variables/Responses/ Constraints/ Objective - DRCO

- Stiffness and volume reduction.
- Solid Isotropic Material with Penalization method – SIMP.
- Two common objective functions.
SPOT-WELD OPTIMIZATION

TOPOLOGY RESULTS – FATIGUE CONSTRAINT

<table>
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<td>Fatigue Life</td>
<td>56</td>
<td>44</td>
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<td></td>
<td>7 040 000</td>
<td>7 152 900</td>
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<td>Fatigue Life</td>
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<td>46</td>
</tr>
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<td></td>
<td>7 040 000</td>
<td>6 970 200</td>
</tr>
</tbody>
</table>
SPOT-WELD OPTIMIZATION

TOPOLOGY RESULTS – MULTIPLE LINEAR CONSTRAINTS
SPOT-WELD OPTIMIZATION

TOPOLOGY RESULTS – MULTIPLE LINEAR CONSTRAINTS

<table>
<thead>
<tr>
<th>Constraint Number</th>
<th>Description</th>
<th>Constr. bound of nom. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>First torsional mode [Hz]</td>
<td>98.78</td>
</tr>
<tr>
<td>2.</td>
<td>First bending mode [Hz]</td>
<td>99.10</td>
</tr>
<tr>
<td>3.</td>
<td>Front end lateral mode [Hz]</td>
<td>99.61</td>
</tr>
<tr>
<td>4.</td>
<td>Steering system Y-mode [Hz]</td>
<td>99.55</td>
</tr>
<tr>
<td>5.</td>
<td>Steering system Z-mode [Hz]</td>
<td>98.54</td>
</tr>
<tr>
<td>6.</td>
<td>Retractor right displacement [mm]</td>
<td>120.0</td>
</tr>
<tr>
<td>7.</td>
<td>Retractor mid displacement [mm]</td>
<td>120.0</td>
</tr>
<tr>
<td>8.</td>
<td>Retractor left displacement [mm]</td>
<td>120.0</td>
</tr>
<tr>
<td>9.</td>
<td>Anchor outboard right displacement [mm]</td>
<td>120.0</td>
</tr>
<tr>
<td>10.</td>
<td>Anchor inboard right displacement [mm]</td>
<td>120.0</td>
</tr>
<tr>
<td>11.</td>
<td>Anchor inboard left displacement [mm]</td>
<td>120.0</td>
</tr>
<tr>
<td>12.</td>
<td>Anchor outboard left displacement [mm]</td>
<td>120.0</td>
</tr>
<tr>
<td>13.</td>
<td>Transverse bending compliance [mm/N]</td>
<td>82.30</td>
</tr>
<tr>
<td>14.</td>
<td>Tunnel bending compliance [mm/N]</td>
<td>86.53</td>
</tr>
<tr>
<td>15.</td>
<td>Rocker bending compliance [mm/N]</td>
<td>77.16</td>
</tr>
<tr>
<td>16.</td>
<td>Fatigue Life [cycles]</td>
<td>93.23</td>
</tr>
</tbody>
</table>
### SPOT-WELD OPTIMIZATION

#### TOPOLOGY RESULTS – MULTIPLE LINEAR CONSTRAINTS

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<thead>
<tr>
<th></th>
<th>Nominal</th>
<th>Opt. fat. Constraint</th>
<th>Opt. all Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Spotwelds</td>
<td>1866</td>
<td>1607</td>
<td>1804</td>
</tr>
<tr>
<td>No. removed welds</td>
<td>0</td>
<td>259</td>
<td>62</td>
</tr>
<tr>
<td>Reduction Percentage</td>
<td>0%</td>
<td>13.88%</td>
<td>3.32%</td>
</tr>
</tbody>
</table>
SPOT-WELD OPTIMIZATION
METHOD & PROBLEM FORMULATION – SIZE

minimize \( f_0 = \sum_{i=1}^{12} l_i \)
subject to \( g_i(x) \leq \overline{g}_i, \ i = 1, \ldots, c. \)
\( l_4 = l_{10} \)
\( l_5 = l_{11} \)
\( l_6 = l_{12} \)
\( l_{1,3,7,9,10,12} \in \{0, 1, 2, 3\} \)
\( l_{2,8,11} \in \{0, 1, 2, \ldots, 8\} \)

**GRSM**

1. Initial Sampling from DOE or Random Process
2. Evaluation
3. Global Sampling
4. Response Surface Based Optimization
5. Response Surface Update
6. Terminating condition satisfied?

**GA**

1. Initial Population from Random Sampling or DOE
2. Fitness Evaluation with the Elitism Policy
3. Generate New Population with Crossover & Mutation
4. Fitness Evaluation with the Elitism Policy
5. Converged
   - Yes
     - Algorithm converged?
     - No
   - Not Converged
     - Yes
       - Stopping Criteria Reached?
       - No
SPOT-WELD OPTIMIZATION
SIZE RESULTS – FATIGUE CONSTRAINT

<table>
<thead>
<tr>
<th>No. of Spot-Welds</th>
<th>Nominal Design</th>
<th>Optimal Design (GRSM)</th>
<th>Optimal Design (GA)</th>
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</thead>
<tbody>
<tr>
<td>Fatigue Life</td>
<td>56</td>
<td>34</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>7 040 000</td>
<td>6 280 000</td>
<td>6 426 641</td>
</tr>
</tbody>
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SPOT-WELD OPTIMIZATION
SIZE RESULTS – MULTIPLE LINEAR CONSTRAINTS

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<th>Optimal Design (GA)</th>
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<tbody>
<tr>
<td>No. of Spot-Welds</td>
<td>56</td>
<td>42</td>
<td>35</td>
</tr>
<tr>
<td>Fatigue Life</td>
<td>7 040 000</td>
<td>6 226 552</td>
<td>7 449 345</td>
</tr>
<tr>
<td>$C_1$</td>
<td>43.85</td>
<td>43.32</td>
<td>42.05</td>
</tr>
<tr>
<td>$C_{br}$</td>
<td>25 806.22</td>
<td>24 968.16</td>
<td>24 453.49</td>
</tr>
<tr>
<td>$C_{br}$</td>
<td>342.07</td>
<td>336.14</td>
<td>330.339</td>
</tr>
<tr>
<td>$F_{n2}$</td>
<td>44.57</td>
<td>44.33</td>
<td>43.52</td>
</tr>
</tbody>
</table>
SPOT-WELD OPTIMIZATION
SIZE RESULTS – CRASH LOAD
SPOT-WELD OPTIMIZATION
SIZE RESULTS – CRASH LOAD

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<thead>
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<th>Optimal Design (GRSM)</th>
<th>Optimal Design (GA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue Life</td>
<td>7 040 000</td>
<td>6 376 042</td>
<td>6 963 131</td>
</tr>
<tr>
<td>$C_f$</td>
<td>43.85</td>
<td>43.33</td>
<td>43.69</td>
</tr>
<tr>
<td>$C_{hr}$</td>
<td>25 806.22</td>
<td>25 154.70</td>
<td>24 597.07</td>
</tr>
<tr>
<td>$C_{bt}$</td>
<td>342.07</td>
<td>335.83</td>
<td>344.49</td>
</tr>
<tr>
<td>$F_{m2}$</td>
<td>44.57</td>
<td>44.33</td>
<td>44.56</td>
</tr>
<tr>
<td>$d$</td>
<td>390.1</td>
<td>386.2</td>
<td>385.58</td>
</tr>
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</table>
SPOT-WELD OPTIMIZATION
VALIDATION OF THE GA METHOD
<table>
<thead>
<tr>
<th>Opt. Meth</th>
<th>Objective</th>
<th>Const.</th>
<th>CPU time</th>
<th>No. of welds</th>
<th>Fatigue Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size, GRSM</td>
<td>Min. Number of welds</td>
<td>Fatigue</td>
<td>6.70hrs</td>
<td>34</td>
<td>6 280 000</td>
</tr>
<tr>
<td>Size, GA</td>
<td>Min. Number of welds</td>
<td>Fatigue</td>
<td>6.70hrs</td>
<td>31</td>
<td>6 420 641</td>
</tr>
<tr>
<td>Topology</td>
<td>Min. Volume fract.</td>
<td>Fatigue</td>
<td>0.12hrs</td>
<td>44</td>
<td>7 152 900</td>
</tr>
<tr>
<td>Topology</td>
<td>Min. Weighted Compl.</td>
<td>Fatigue</td>
<td>0.07hrs</td>
<td>46</td>
<td>6 970 200</td>
</tr>
<tr>
<td>Size, GRSM</td>
<td>Min. Number of welds</td>
<td>All linear</td>
<td>13.0hrs</td>
<td>44</td>
<td>6 376 042</td>
</tr>
<tr>
<td>Size, GA</td>
<td>Min. Number of welds</td>
<td>All linear</td>
<td>13.3hrs</td>
<td>46</td>
<td>6 963 131</td>
</tr>
<tr>
<td>Topology</td>
<td>Min. Volume fract.</td>
<td>All linear</td>
<td>0.44hrs</td>
<td>48</td>
<td>7 052 300</td>
</tr>
<tr>
<td>Topology</td>
<td>Min. Weighted Compl.</td>
<td>All linear</td>
<td>0.06hrs</td>
<td>50</td>
<td>6 760 200</td>
</tr>
</tbody>
</table>
ACM, CWELD and Beam all viable for modelling purposes.
ACM less sensitive to mesh size and better stiffness representation.
Nominal stress approach insufficient for fatigue prediction.
Rupp’s structural stress approach renders feasible fatigue life results.

Fatigue life very sensitive to weld distribution.
Topology Optimization quick and easy to setup but limited:
• Linear Static, Single Fatigue Load-Case.
• Global Convergence requires convexity.
• Semi-discrete results.
Size Optimization good for exploratory studies, fine tuned optimization but very computationally expensive.
GRSM method preferred when evaluating spot-weld fatigue life.
QUESTIONS