Bulging between Rolls in Continuously-cast Slabs

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Acknowledgments

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AK Steel
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Inland Steel
LTV Steel
Stollberg, Inc.

National Center for Supercomputing Applications (NCSA)
Outline

- Introduction
- Modeling methodology
- Multiple-roll pitch model
  - Effect of roll misalignment
  - Effect of sudden roll pitch change
- Parametric study
  - Plain carbon steel
  - Stainless steel
- Evaluation of empirical bulging prediction equations
- Applications
**Introduction**

- **Bulging** of continuously cast steel slabs between supporting rolls is caused by internal ferrostatic pressure acting on the solidifying strand shell due to the weight of liquid steel and the height from the meniscus.
  
  - Bulging is directly responsible for internal cracks, centerline segregation, and permanent deformation, which lead to poor quality of the continuously cast products.
  
  - The bulging of slabs can also cause an increase of the load transmitted to the rolls and enhance their rate of wear.

- In practice, it is important to estimate bulging quantitatively in continuous caster design and set-up of secondary cooling conditions, especially in high-speed casting.
Background

The Continuous Casting Process
(Acknowledgement to Prof. Brian G. Thomas)

2D FEM single roll pitch model for bulging

- FEM Domain with 60x16 mesh
- Periodic B.C. on two ends
  (coupled X & Y displacement)
Key Phenomena

- Roll pitch and shell thickness have a paramount effect on bulging
- Negative bulging
- Slab movement
- Transient behavior due to roll pitch changes
- Effect of temperature profile on bulging
- Material property at high temperature
- Creep behavior
Modeling Methodology

- 2-D Finite Element Method thermal stress model with Lagrangian approach is developed using commercial FEM package ABAQUS.
  - Stress analysis
  - Nonlinear problem

- Simplifying Assumptions:
  - 2-D elastic-plastic model with plane stress assumption
  - Constant solidified shell thickness
  - Uniform ferrostatic pressure along x
  - Constant temperature gradient across the shell thickness with uniform temperature profile along x
Define the Problem

Objectives:
1. Suddenly drop one roll and keep other rolls moving as usual, what is the difference from uniform roll pitch model?
2. What is the effect of roll misalignment on bulging?
3. Reproduce the simulation done by Gancarz, Lamant, et al. Is their simulation correct?

Multiple roll pitch bulging model (with at least 4 roll pitches)

Experimental bulging profile on Sumitomo and Calculations over 9 rolls done by Gancarz, Lamant, et al.
Wunnenberg Conditions for Bulging Calculation

- **Wunnenberg Conditions**
  
  Slab width = 1350 mm  
  Roll pitch = 860 mm  
  Shell thickness = 79 mm
  
  $T_{\text{Liquidus}} = 1500^\circ C$  
  $T_{\text{Surface}} = 1000^\circ C$
  
  Liquid steel density = 7000 kg/m$^3$
  
  Distance from meniscus = 3.9 m
  
  Ferrostatic pressure = 0.26 MPa
  
  Casting speed = 0.85 m/min (14.2 mm/s)

- **Wunnenberg Measurements** - The bulging profile is asymmetric with maximum deflection of 6.5mm at 75% from upstream roll.

<table>
<thead>
<tr>
<th>Distance from upstream roll</th>
<th>@25%</th>
<th>@50%</th>
<th>@75%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (mm)</td>
<td>3.0</td>
<td>5.7</td>
<td>6.5 (max)</td>
</tr>
</tbody>
</table>
Strain contour plot for a typical single roll pitch model

Total Strain in X direction

DISPLACEMENT MAGNIFICATION FACTOR = 8.00
RESTART FILE = c2 STEP 157 INCREMENT 1
TIME COMPLETED IN THIS STEP 1.01 TOTAL ACCUMULATED TIME 304.
ABAQUS VERSION: 5.8-1 DATE: 05-APR-2000 TIME: 17:16:27
Strain contour plot for an 8-roll 430mm pitch model with one roll missing

Total Strain in X direction

8-roll 430mm pitch model with one roll missing

DISPLACEMENT MAGNIFICATION FACTOR = 20.0
RESTART FILE = miss4 STEP 187 INCREMENT 11
TIME COMPLETED IN THIS STEP 1.01 TOTAL ACCUMULATED TIME 334.
ABAQUS VERSION: 5.8-1 DATE: 01-NOV-1999 TIME: 15:59:07
Comparison of Bulging Profile between uniform roll pitch and sudden roll pitch change

- Sudden roll pitch change leads to larger Max bulge and much larger Negative bulge, but the change in Max tensile strain on solidification front is not as significant as that of Max bulge and Neg bulge.
- Maximum bulge is at about 60% of the roll pitch from the upstream roll.
- Transient effect of sudden roll pitch change settles down in the following 4~5 roll pitches.

<table>
<thead>
<tr>
<th></th>
<th>Uniform 860mm roll pitch</th>
<th>430mm roll pitch with one roll missing</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum bulge</td>
<td>10.61 mm</td>
<td>18.57 mm</td>
<td>75 %</td>
</tr>
<tr>
<td>Negative bulge</td>
<td>2.90 mm</td>
<td>7.30 mm</td>
<td>152 %</td>
</tr>
<tr>
<td>Max strain on sol. front</td>
<td>2.32 %</td>
<td>2.62 %</td>
<td>12.9 %</td>
</tr>
</tbody>
</table>
- Negative bulge is important to tensile strain on solidification front, which is responsible for internal crack.
- Maximum tensile strain is located between maximum bulge and negative bulge, but not on maximum negative bulge point.
Effect of Misalignment on Bulging

Surface Displacement (mm) vs X (mm)

Roll Pitch = 430 mm

Effective Maximum Misalignment = 17.43 mm

- 1mm misalignment
- 2mm misalignment
- 3mm misalignment
- 5mm misalignment
- 10mm misalignment
- 15mm misalignment
- Infinity misalignment

Maximum bulging:
- Effective max misalignment
Effect of Misalignment on Bulge and Max Strain on Solidification Front

- Max bulge, Negative bulge and Max strain on solidification front are almost linear functions of misalignment till effective maximum misalignment (17.43mm).
- When actual misalignment is larger than effective maximum misalignment, it behaves like one roll is missing.
# Effect of Misalignment on Bulging

<table>
<thead>
<tr>
<th>Misalignment (mm)</th>
<th>Maximum bulge (mm)</th>
<th>Position from upstream roll</th>
<th>Negative bulge (mm)</th>
<th>Ratio of neg. bulge to max bulge</th>
<th>Max strain on solidification front (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Roll spacing 430mm)</td>
<td>0.11</td>
<td>51.6%</td>
<td>0</td>
<td>0</td>
<td>0.046</td>
</tr>
<tr>
<td>1</td>
<td>1.05</td>
<td>54.2%</td>
<td>0.09</td>
<td>0.085</td>
<td>0.131</td>
</tr>
<tr>
<td>2</td>
<td>2.08</td>
<td>54.2%</td>
<td>0.34</td>
<td>0.163</td>
<td>0.249</td>
</tr>
<tr>
<td>3</td>
<td>3.12</td>
<td>55.8%</td>
<td>0.71</td>
<td>0.227</td>
<td>0.360</td>
</tr>
<tr>
<td>5</td>
<td>5.26</td>
<td>57.5%</td>
<td>1.64</td>
<td>0.312</td>
<td>0.686</td>
</tr>
<tr>
<td>10</td>
<td>10.65</td>
<td>59.2%</td>
<td>4.13</td>
<td>0.388</td>
<td>1.49</td>
</tr>
<tr>
<td>15</td>
<td>16.03</td>
<td>59.2%</td>
<td>6.38</td>
<td>0.398</td>
<td>2.28</td>
</tr>
<tr>
<td>∞ (One roll missing)</td>
<td>18.57</td>
<td>59.2%</td>
<td>7.30</td>
<td>0.393</td>
<td>2.62</td>
</tr>
<tr>
<td>Double roll spacing 860mm</td>
<td>10.61</td>
<td>64.2%</td>
<td>2.90</td>
<td>0.273</td>
<td>2.32</td>
</tr>
</tbody>
</table>
Sumitomo Conditions

Pilot caster at Sumitomo Metals in Japan

- 400 x 100 mm² slab
- Casting Speed = 1.65 m/min
- Caster Radius (R) = 3 m
- Mold Length = 0.7 m
- Roll Pitch (L) = 310 mm
- Shell Thickness (D) = 23.17 mm
- Height from Meniscus (H) = 2.65 m
- Ferrostatic Pressure = 0.18 MPa
- Surface Temperature = 1220 °C

=> Distance from Meniscus = 3.25 m

\[
\text{# of rolls} = \frac{3.25 - 0.7}{0.31} \approx 8
\]

The point of interest is around 8-9 rolls down the mold.

Measurement:

1. Maximum bulging of 3.2 mm is at 60~65% of the roll pitch from the upstream roll.
2. There is a negative bulging at the vicinity of the supporting rolls.
3. The ratio between negative bulging and positive bulging is around 0.4.
Strain contour plot for roll pitch changing from 250mm to 310mm

Total Strain in X direction

Roll pitch changing from 250mm to 310mm

DISPLACEMENT MAGNIFICATION FACTOR = 70.0
RESTART FILE = continue7
TIME COMPLETED IN THIS STEP 1.01 TOTAL ACCUMULATED TIME 463.
ABAQUS VERSION: 5.8-1 DATE: 18-JAN-2000 TIME: 10:32:46
Comparison of Bulging Profile
between uniform roll pitch and sudden roll pitch change

- Sudden roll pitch change from 250mm to 310mm
- Uniform 310mm roll pitch

Surface Displacement (mm)

Distance x (mm)
Bulging Profile on Surface and Strain Profile on Solidification Front

Surface Displacement (mm)

Strain on Solidification Front (%)

Distance x (mm)
Observations

- Current model qualitatively matches Sumitomo measurements and simulation by J. Gancarz, et al.

<table>
<thead>
<tr>
<th></th>
<th>Sudden change of roll pitch from 250mm to 310mm</th>
<th>Uniform 310mm roll pitch</th>
<th>Increase (sudden/uniform)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sumitomo measurements</td>
<td>4.6 mm</td>
<td>3.2 mm</td>
<td>44%</td>
</tr>
<tr>
<td>J. Gancarz et al. model</td>
<td>3.6 mm</td>
<td>2.0 mm</td>
<td>80%</td>
</tr>
<tr>
<td>Our model</td>
<td>5.96 mm</td>
<td>3.67 mm</td>
<td>62%</td>
</tr>
</tbody>
</table>

* Surface temperature changed from 1220 °C to 1000 °C to account for property uncertainty.

- Sudden roll pitch change leads to a larger bulge and bigger tensile strain on solidification front.

<table>
<thead>
<tr>
<th></th>
<th>Uniform 250mm</th>
<th>Sudden change from 250mm to 310mm</th>
<th>Uniform 310mm</th>
<th>Increase (sudden/uniform)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum bulge</td>
<td>0.34 mm</td>
<td>5.96 mm</td>
<td>3.67 mm</td>
<td>62%</td>
</tr>
<tr>
<td>Negative bulge</td>
<td>0 mm</td>
<td>1.78 mm</td>
<td>0.93 mm</td>
<td>91%</td>
</tr>
<tr>
<td>Max strain on sol. front</td>
<td>0.2%</td>
<td>2.1%</td>
<td>1.75%</td>
<td>20%</td>
</tr>
</tbody>
</table>

- Disturbance from upstream rolls settles down (within 2%) after 4 roll pitches.
- Maximum tensile strain on solidification front is located on top of the rolls, instead of maximum negative bulge.
Temperature dependent stress-strain curves for plain carbon steel

Experimental data (\%C, strain rate(s\(^{-1}\)), temperature)
- Wray data (0.051\%C, 2.4e-3, 950 °C)
- Wray data (0.051\%C, 2.9e-3, 1100 °C)
- Wray data (0.93\%C, 2.3e-3, 1200 °C)
- Suzuki data (0.25\%C, 6.7e-3, 1000 °C)
- Suzuki data (0.25\%C, 6.7e-3, 1100 °C)
- Suzuki data (0.25\%C, 6.7e-3, 1200 °C)
- Suzuki data (0.25\%C, 6.7e-3, 1300 °C)
- Suzuki data (0.25\%C, 6.7e-3, 1400 °C)
- Suzuki data (0.25\%C, 6.7e-3, 1500 °C)

Linear kinematic hardening model in ABAQUS

This work (950 °C)
This work (1100 °C)
This work (1200 °C)
This work (1400 °C)
This work (1500 °C)
Roll Pitch Study

\[ d_{\text{max}} = c_1 \cdot L^{6.34} \]

Bulging Displacement, \( d_{\text{max}} \) (mm)

Roll Pitch, \( L \) (mm)

- \( d_{\text{max}} \) is the maximum bulging displacement.
- The graph shows a linear relationship between the roll pitch and the bulging displacement, with a power law exponent of 6.34.

- The standard Wunnenberg condition is represented by a specific point on the graph.
Shell Thickness Study

\[ d_{\text{max}} = c_2 \cdot D^{5.62} \]

Graph showing the relationship between Shell Thickness, \( D \) (mm), and Bulging Displacement, \( d_{\text{max}} \) (mm). The relationship is shown as a power law where \( d_{\text{max}} \) is inversely proportional to \( D \) raised to the power of 5.62. The graph includes data points and a dashed line representing the Standard Wunnenberg Condition.
Ferrostatic Pressure Study

\[ d_{\text{max}} = c_3 \times P^{1.99} \]

- Dashed line: Bulging Displacement (mm)
- Dot: Standard Wunnenberg Condition

Bulging Displacement, \( d_{\text{max}} \) (mm) vs. Ferrostatic Pressure, \( P \) (MPa)
Surface Temperature Study

Bulging Displacement, $d_{\text{max}}$ (mm)

Surface Temperature, $T_{\text{surf}}$ (°C)

$d_{\text{max}} = c_4 \times T_{\text{surf}}^{8.735}$

Standard Wunnenberg Condition
Bulging Prediction Equation

- 2-D shape factor from Okamura

\[ F(W / L) = 1 - \left\{ \frac{\pi W}{2L} \tanh(\pi W / 2L) + 2 \right\} / 2 \cosh(\pi W / 2L) \]

- Bulging prediction equation based on the parametric study for plain carbon steel

\[ d_{max} (mm) = 1.0374 \times 10^{-32} F(W / L) \frac{L_{(mm)}^{6.3403} P_{(MPa)}^{-1.9931} T_{surf}^{8.735}}{D_{(mm)}^{5.6181}} \]

- To be improved:
  - Casting speed
  - Material properties
Temperature dependent stress-strain curves for stainless steel

Experimental data for stainless steel (430) [1] at strain rate of $6.67 \times 10^{-4}$

Armco Case Study

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll pitch, L (mm)</td>
<td>330</td>
<td>165</td>
<td>165</td>
</tr>
<tr>
<td>Shell thickness, D (mm)</td>
<td>12</td>
<td>17</td>
<td>28.3</td>
</tr>
<tr>
<td>Ferrostatic pressure, P (MPa)</td>
<td>0.0223</td>
<td>0.0446</td>
<td>0.1235</td>
</tr>
<tr>
<td>Surface temperature, $T_{surf}$ (°C)</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>$d_{max}$ (mm)</td>
<td>0.6548</td>
<td>0.0240</td>
<td>0.0184</td>
</tr>
<tr>
<td>Plain carbon steel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainless steel</td>
<td>8.88</td>
<td>0.0315</td>
<td>0.0287</td>
</tr>
<tr>
<td>Our Equation</td>
<td>6.8256</td>
<td>0.0474</td>
<td>0.0206</td>
</tr>
</tbody>
</table>

- Material property has a paramount effect on bulging
Case 1 (330mm roll pitch)

- Surface strain ranging from –0.8%~0.4%
- Average strain rate is around 6.67x10^{-4} s^{-1}
Evaluation of Empirical Bulging Prediction Equations

- **Okamura Equation** (based on FEM simulations):
  \[ d_{\text{max}}, \epsilon_b = AF(W / L)D^j P^k L^m T_{\text{surf}}^n V_c^n \]
  Where, \( F(W / L) = 1 - \{(\pi W / 2L) \tanh(\pi W / 2L) + 2\}/2 \cosh(\pi W / 2L) \)

- **Palmaers Equation** (based on beam bending analysis):
  \[ d_{\text{max}} = 0.4623C(T_{\text{surf}}) \frac{P^{1.5} L^{5.12}}{V_c^{0.22} D^{3.8}} \]
  where, \( C(T_{\text{surf}}) = \begin{cases} 
 0.609 \times 10^{-4} & T_{\text{surf}} = 900^\circ \text{C} \\
 0.725 \times 10^{-4} & T_{\text{surf}} = 1000^\circ \text{C} \\
 0.929 \times 10^{-4} & T_{\text{surf}} = 1100^\circ \text{C} 
\end{cases} \)

- **Lamant Equation** (based on beam bending analysis):
  \[ d_{\text{max}} = 7.4088 \times 10^{-14} \exp(0.003866(T_{\text{surf}} + 273)) \frac{L^{7.16} H^{2.18}}{V_c^{0.4} D^{5.47}} \]
Comparison of Different Models

<table>
<thead>
<tr>
<th></th>
<th>Wunnenberg case (860mm)</th>
<th>Sumitomo case (310mm)</th>
<th>Armco case 3 (165mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Okamura Equation</td>
<td>1.4985</td>
<td>0.4680</td>
<td>0.0012</td>
</tr>
<tr>
<td>Palmaers Equation</td>
<td>10.2025</td>
<td>3.5596 *</td>
<td>0.0332</td>
</tr>
<tr>
<td>Lamant Equation</td>
<td>9.0123</td>
<td>3.8384</td>
<td>0.0033</td>
</tr>
<tr>
<td>Our Equation</td>
<td>6.256</td>
<td>3.5667 **</td>
<td>0.0206</td>
</tr>
<tr>
<td>Our model (raw / adjusted)</td>
<td>10.61 / 6.64</td>
<td>3.67 / 1.79 **</td>
<td>0.0184 / 0.0184</td>
</tr>
<tr>
<td>Measurement</td>
<td>5~7</td>
<td>3.2</td>
<td>N/A</td>
</tr>
</tbody>
</table>

* Must use surface temperature = 1100 °C instead of 1220 °C, so prediction is really higher.
** Surface temperature of 1000 °C is used instead of 1220 °C.

Conclusion:
- Okamura Equation is always much too low.
- Lamant Equation is ok except for Armco case 3 (too low).
- Palmaers Equation matches measurements and our model pretty well.
Future Work

- Need more appropriate material properties at high temperature for each individual case
- Results should be more quantitative
- Applications
  - Crack formation
  - Slab width prediction
Slab Width Prediction

Possible slab distortion mechanisms
- Creep due to ferrostatic pressure
- Bulging ratcheting effect
  - Ferrostatic pressure
  - Roll distortion
- Roll friction / thermal shrinkage ratcheting
- Narrow face bulging
### Bulging Calculation and Slab Width Change

<table>
<thead>
<tr>
<th>Roll number</th>
<th>Predicted bulging displacement (mm)</th>
<th>Slab width change due to bulging (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.11942</td>
<td>1.5281e-05</td>
</tr>
<tr>
<td>2</td>
<td>0.28486</td>
<td>0.00017581</td>
</tr>
<tr>
<td>3</td>
<td>0.24819</td>
<td>0.00012889</td>
</tr>
<tr>
<td>4</td>
<td>0.20443</td>
<td>8.1362e-05</td>
</tr>
<tr>
<td>5</td>
<td>0.17293</td>
<td>5.2825e-05</td>
</tr>
<tr>
<td>6</td>
<td>0.14554</td>
<td>3.1893e-05</td>
</tr>
<tr>
<td>7</td>
<td>0.13665</td>
<td>2.5867e-05</td>
</tr>
<tr>
<td>8</td>
<td>0.23562</td>
<td>0.00011430</td>
</tr>
<tr>
<td>9</td>
<td>0.31711</td>
<td>0.00022241</td>
</tr>
<tr>
<td>10</td>
<td>0.25355</td>
<td>0.00013535</td>
</tr>
<tr>
<td>11</td>
<td>0.21009</td>
<td>8.6989e-05</td>
</tr>
<tr>
<td>12</td>
<td>0.18969</td>
<td>6.7413e-05</td>
</tr>
<tr>
<td>13</td>
<td>0.15023</td>
<td>3.5219e-05</td>
</tr>
<tr>
<td>14</td>
<td>0.11892</td>
<td>1.4990e-05</td>
</tr>
<tr>
<td>15</td>
<td>0.27250</td>
<td>0.00015928</td>
</tr>
<tr>
<td>16</td>
<td>0.58235</td>
<td>0.00079506</td>
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<tr>
<td>17</td>
<td>0.49881</td>
<td>0.00057825</td>
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<td>18</td>
<td>0.42561</td>
<td>0.00041583</td>
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<tr>
<td>19</td>
<td>0.37769</td>
<td>0.00032345</td>
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<tr>
<td>20</td>
<td>0.33457</td>
<td>0.00024972</td>
</tr>
<tr>
<td>21</td>
<td>0.50388</td>
<td>0.00059045</td>
</tr>
<tr>
<td>22</td>
<td>0.24225</td>
<td>0.00012191</td>
</tr>
<tr>
<td>23</td>
<td>0.20463</td>
<td>8.1553e-05</td>
</tr>
<tr>
<td>24</td>
<td>0.17266</td>
<td>5.2606e-05</td>
</tr>
<tr>
<td>25</td>
<td>0.15376</td>
<td>3.7792e-05</td>
</tr>
<tr>
<td>26</td>
<td>0.13770</td>
<td>2.6560e-05</td>
</tr>
<tr>
<td>27</td>
<td>0.23118</td>
<td>0.00010933</td>
</tr>
<tr>
<td>28</td>
<td>0.12053</td>
<td>1.5919e-05</td>
</tr>
<tr>
<td>29</td>
<td>0.11656</td>
<td>1.3658e-05</td>
</tr>
<tr>
<td>30</td>
<td>0.10718</td>
<td>8.6223e-06</td>
</tr>
<tr>
<td>31</td>
<td>0.10097</td>
<td>5.5177e-06</td>
</tr>
<tr>
<td>32</td>
<td>0.095060</td>
<td>2.7379e-06</td>
</tr>
<tr>
<td>33</td>
<td>0.17286</td>
<td>5.2766e-05</td>
</tr>
<tr>
<td>34</td>
<td>0.17696</td>
<td>5.6210e-05</td>
</tr>
<tr>
<td>35</td>
<td>0.16001</td>
<td>4.2505e-05</td>
</tr>
<tr>
<td>36</td>
<td>0.13810</td>
<td>2.6825e-05</td>
</tr>
<tr>
<td>37</td>
<td>0.11896</td>
<td>1.5017e-05</td>
</tr>
<tr>
<td>38</td>
<td>0.13535</td>
<td>2.5019e-05</td>
</tr>
<tr>
<td>39</td>
<td>0.090328</td>
<td>6.3209e-07</td>
</tr>
</tbody>
</table>

Accumulated slab width change = 0.004978 mm

Mold width = 1111.0 mm
Measured slab width = 1138.5 mm

Narrow face bulging = 7.9 mm
Thermal shrinkage = 7.3 mm
Accumulated slab width change due to bulging = 0.005 mm