FEM Analysis of Bulging between Rolls in Continuous Casting

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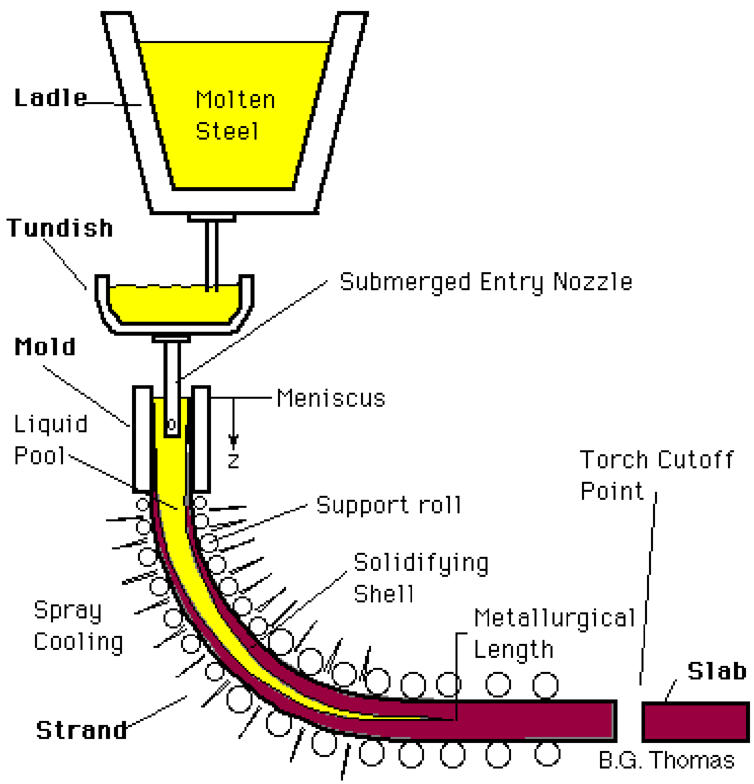
Introduction

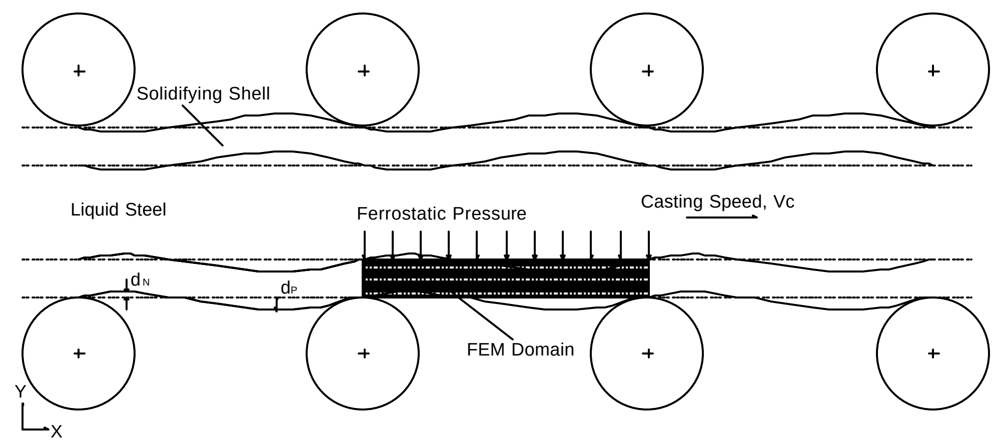
- ***Bulging*** of continuously cast steel slabs between supporting rolls is caused by internal ferrostatic pressure acting on the solidifying strand shell due to the weight of liquid steel and the height from the meniscus.
  – Bulging is directly responsible for internal cracks, centerline segregation, 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

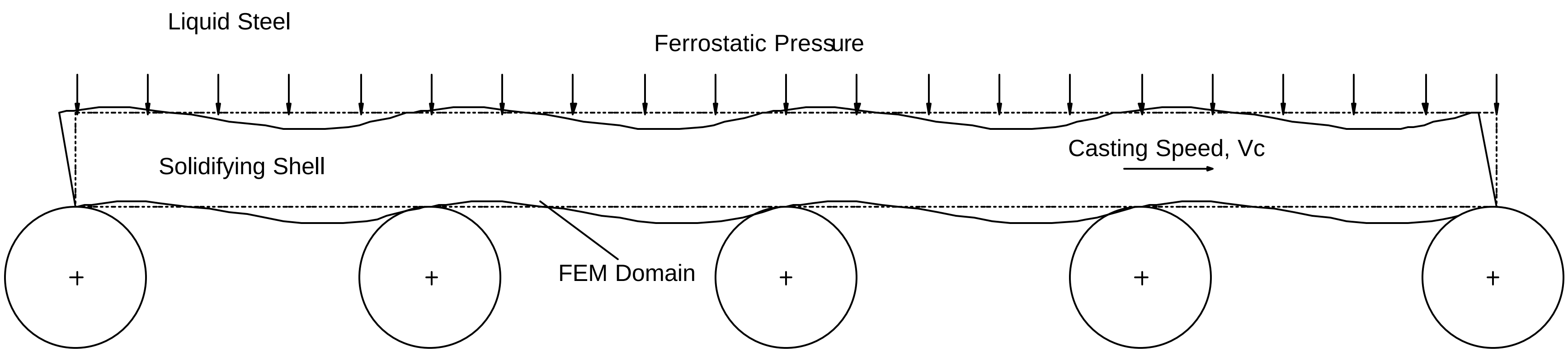
(Acknowledgement to Prof. Brian G. Thomas)



2D FEM single roll pitch model for bulging

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

Define the Problem



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

Objectives:

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

Experimental bulging profile on Sumitomo and
Calculations over 9 rolls done by Gancarz, Lamant, et al.

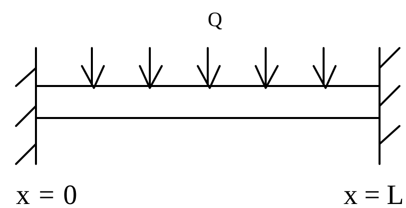
Formal Scaling Analysis

- After formal scaling,

$$y^* = \frac{PL^4}{ED^4}\left(-\frac{1}{2}x^{*2} + x^{*3} - \frac{1}{2}x^{*4}\right)$$

$$y^*_{\max} = y^*\left(x^* = \frac{1}{2}\right) = -\frac{1}{32}\frac{PL^4}{ED^4}$$

$$y_{\max} = y^*_{\max} D = -\frac{1}{32}\frac{PL^4}{ED^3}$$



Beam Bending Theory (elasto-static)

E – Elastic Modulus

P – Pressure

W – Slab width

D – Thickness

L – Length

Q – Load density (Load per unit length), Q=PW

- Conclusions:
  - Slab width (W) is cancelled during formal scaling, so it is justification for making a 2D assumption. Although narrow face will provide extra support to the slab, that effect will be taken into account by a function of aspect ratio of slab width to roll pitch.
  - Roll pitch (L) and shell thickness (D) play an important role on bulging:

$$y_{\max} \propto L^4, y_{\max} \propto \frac{1}{D^3}$$

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

Wunnenberg Conditions for Bulging Calculation

- Wunnenberg Conditions

  Slab width = 1350 mm　　Roll pitch = 860 mm

  Shell thickness = 79 mm

  $T_{Liquidus}$ = 1500 $°C$　　$T_{Surface}$ = 1000 $°C$

  Liquid steel density = 7000 kg/m^3

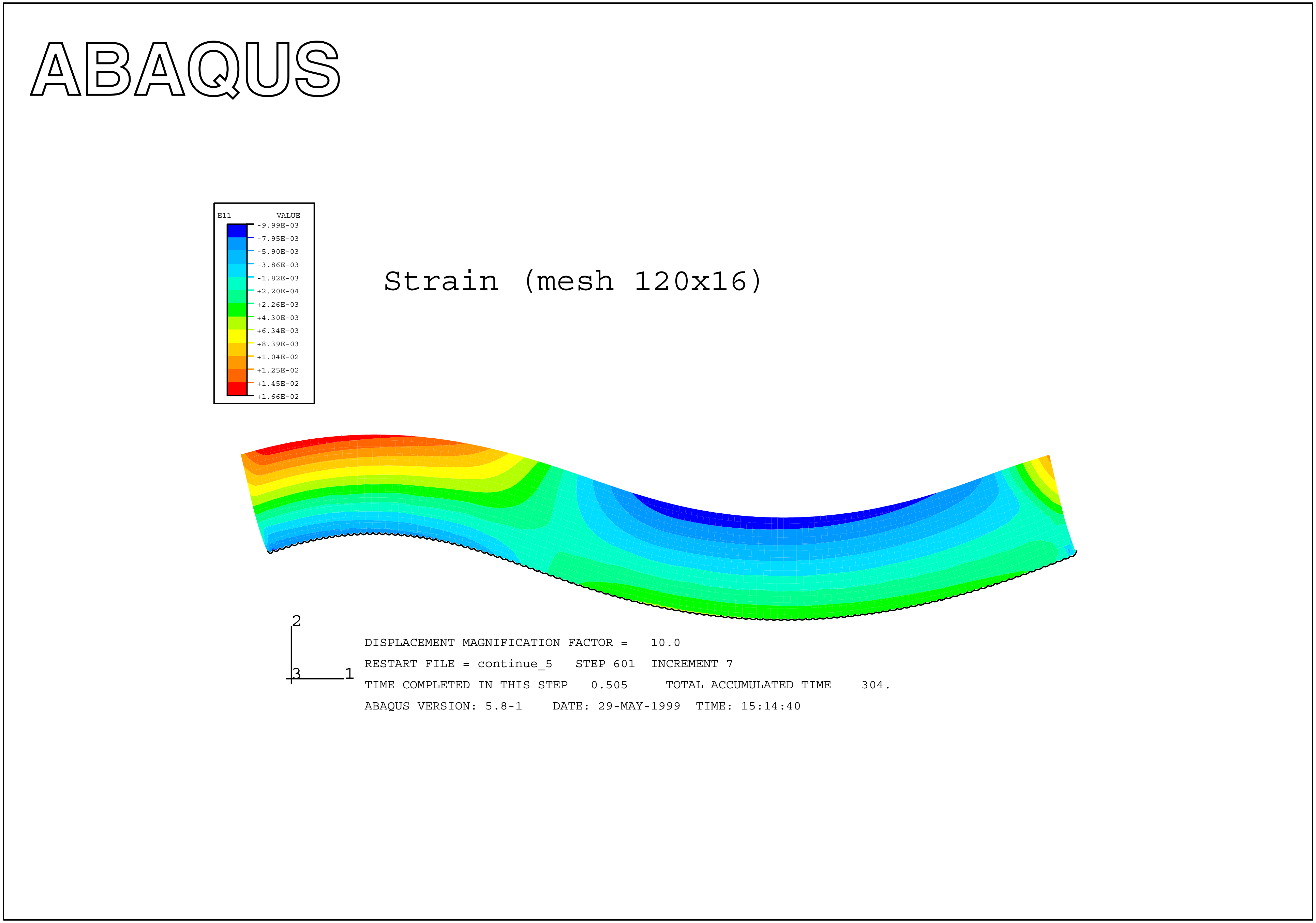
  Distance from meniscus = 3.9 m

  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.

Distance from upstream roll	@25%	@50%	@75%
Displacement (mm)	3.0	5.7	6.5(max)


ABAQUS
E11 VALUE
-9.99E-03
-7.95E-03
-5.90E-03
-3.86E-03
-1.82E-03
+2.20E-04
+2.26E-03
+4.30E-03
+6.34E-03
+8.39E-03
+1.04E-02
+1.25E-02
+1.45E-02
+1.66E-02
Strain (mesh 120x16)
2
3
1
DISPLACEMENT MAGNIFICATION FACTOR = 10.0
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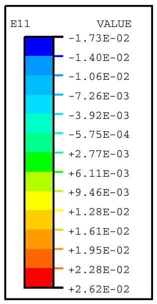
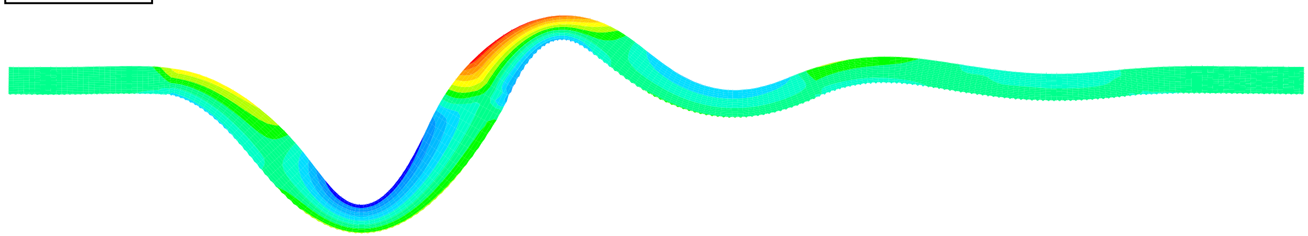
TIME COMPLETED IN THIS STEP 0.505 TOTAL ACCUMULATED TIME 304.
ABAQUS VERSION: 5.8-1 DATE: 29-MAY-1999 TIME: 15:14:40

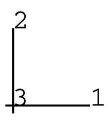
ABAQUS

(8) 430mm roll pitches with one roll missing
(infinity misalignment)

Strain Contour Plot







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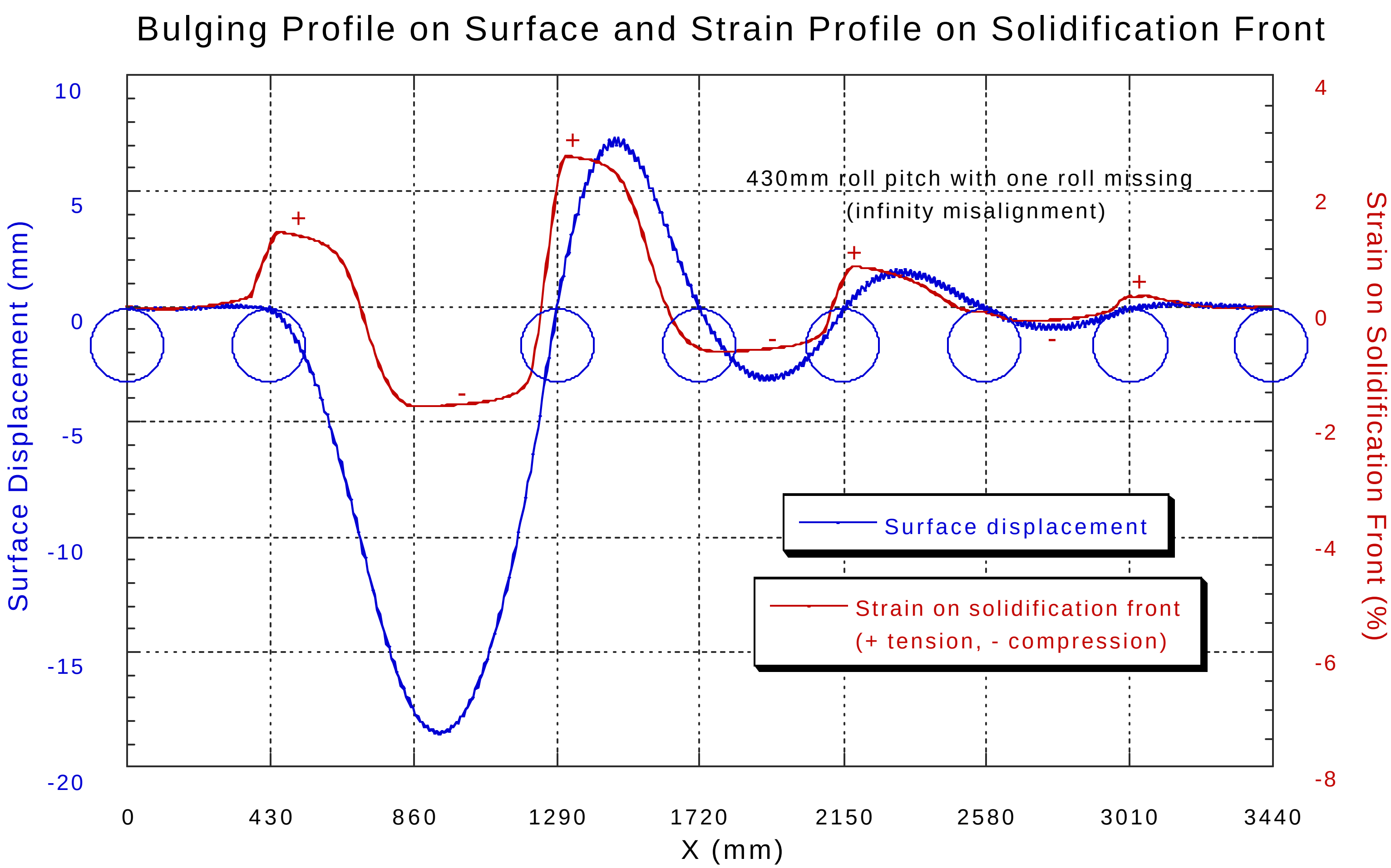
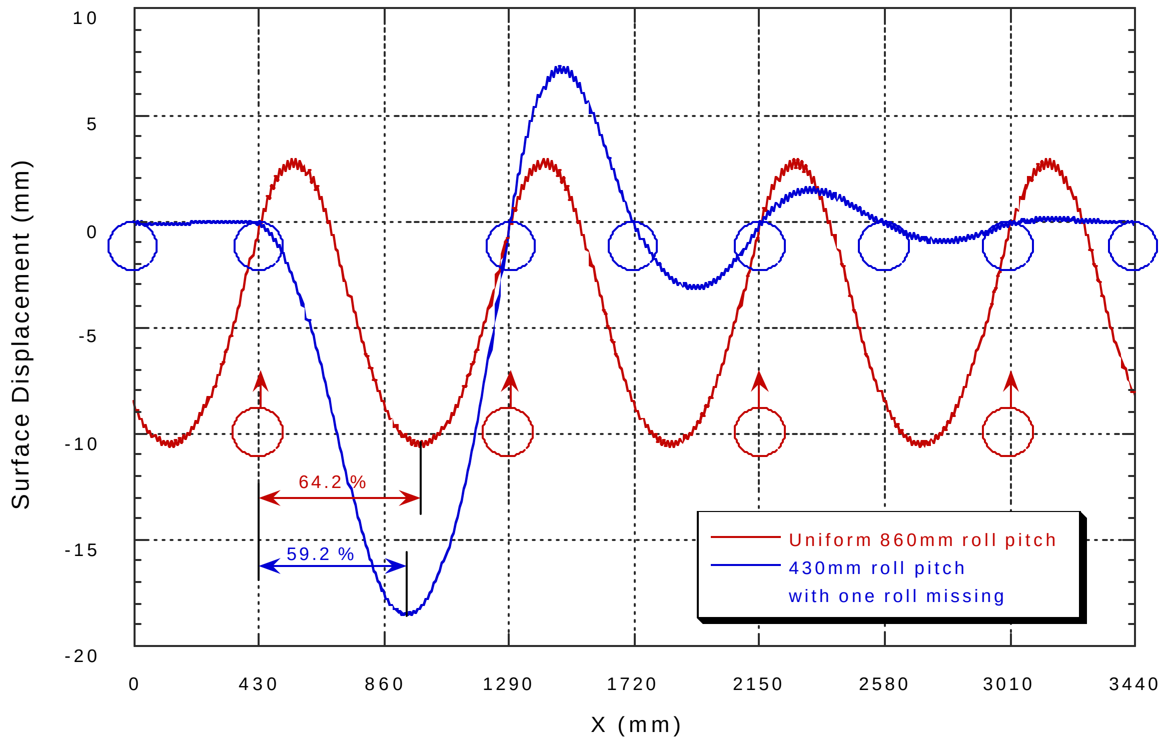


- Negative bulge is important to tensile strain on solidification front, which is responsible for internal crack.
- Maximum tensile strain is located between maximum bulge and negative bulge, but not on maximum negative bulge point.

Comparison of Bulging Profile
between uniform roll pitch and sudden roll pitch change



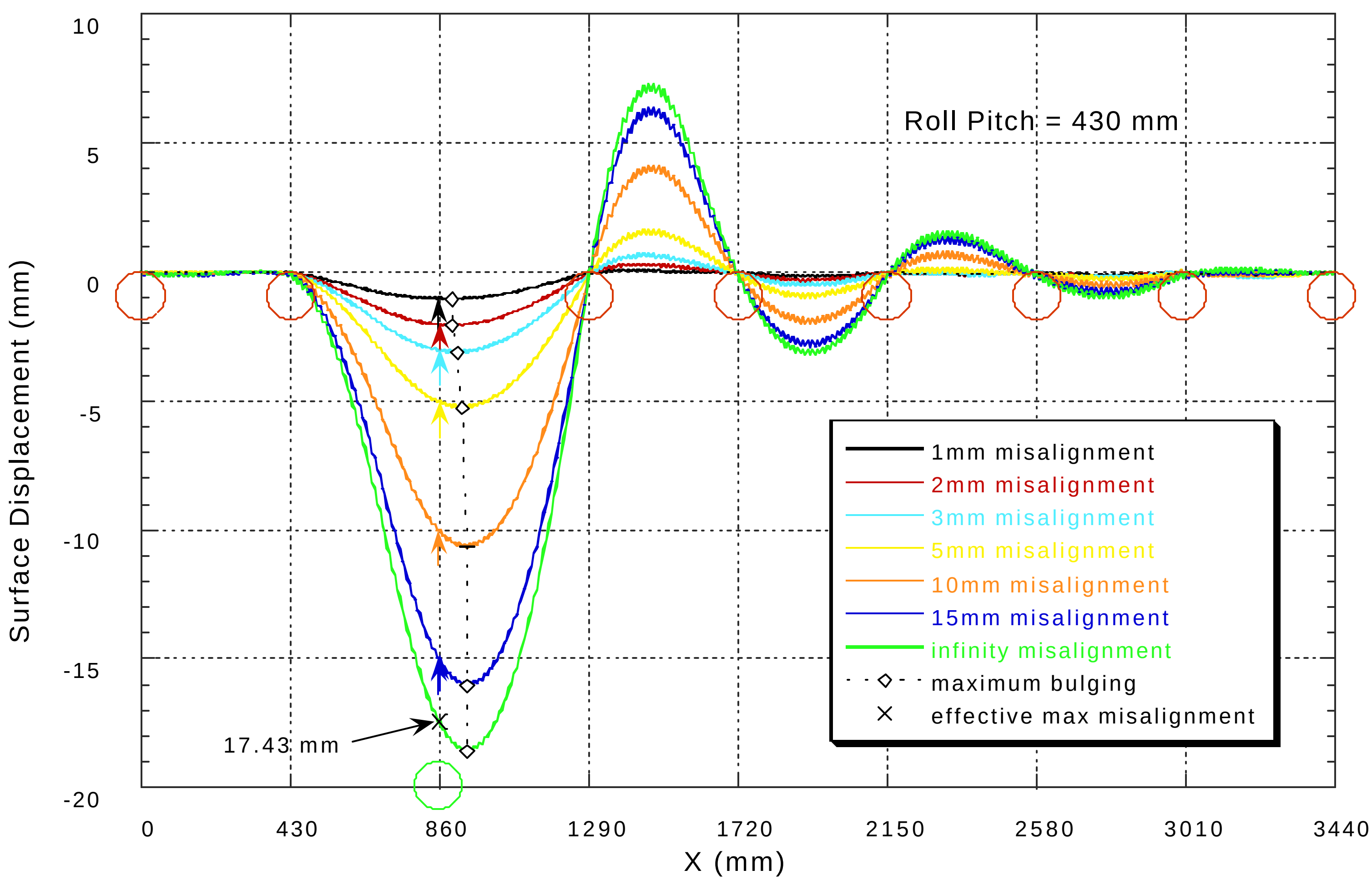
	Uniform 860mm roll pitch	430mm roll pitch with one roll missing	Difference
Maximum bulge	10.61 mm	18.57 mm	75 %
Negative bulge	2.90 mm	7.30 mm	152 %
Max strain on sol. front	2.32 %	2.62 %	12.9 %

- 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.

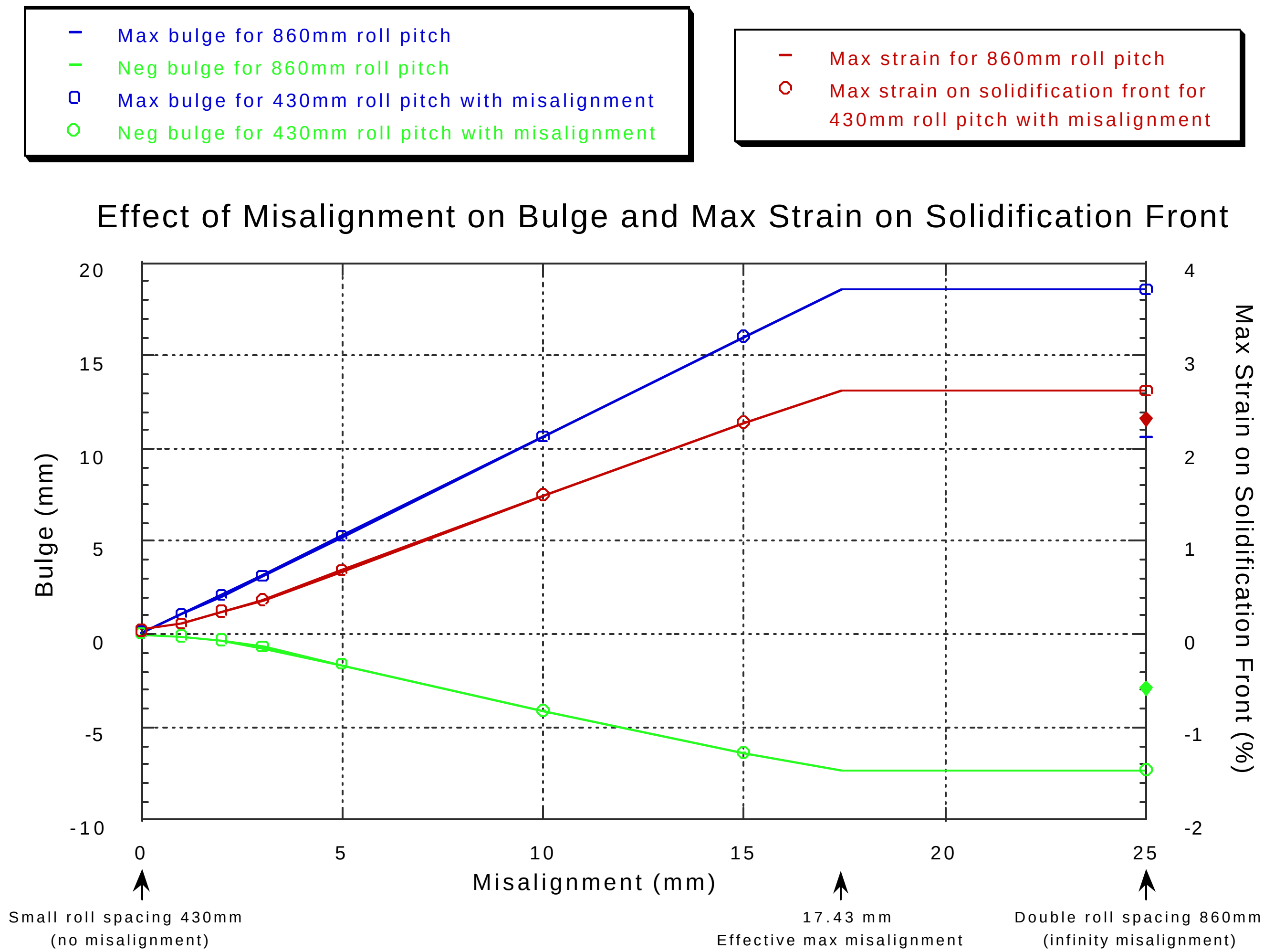
Effect of Misalignment on Bulging

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

Effect of Misalignment on Bulging



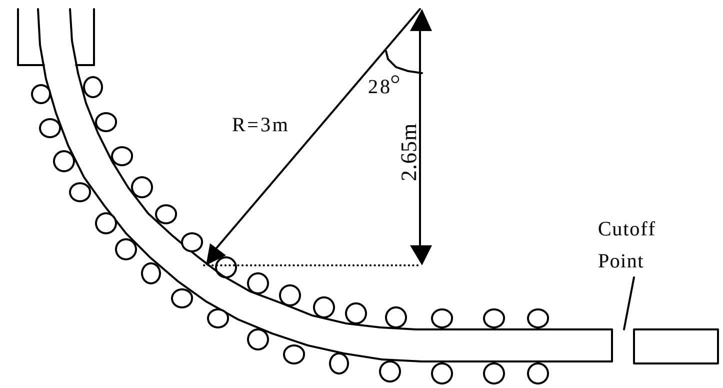
Effective Maximum Misalignment = 17.43 mm



- 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.

Sumitomo Condition

Pilot caster at Sumitomo Metals in Japan



400 x 100 mm^2 slab

Casting Speed = 1.65 m/min

Caster Radius (R) = 3 m

Mold Length = 0.7 m

Roll Pitch (L) = 310 mm

Height from Meniscus (H) = 2.65 m

Ferrostatic pressure = 0.18 MPa

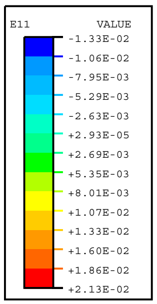
=> Distance from Meniscus = 3.25 m

\# of rolls $= \dfrac{3.25 - 0.7}{0.31} \approx 8$, the point of interest is around 8-9 rolls down the mold.

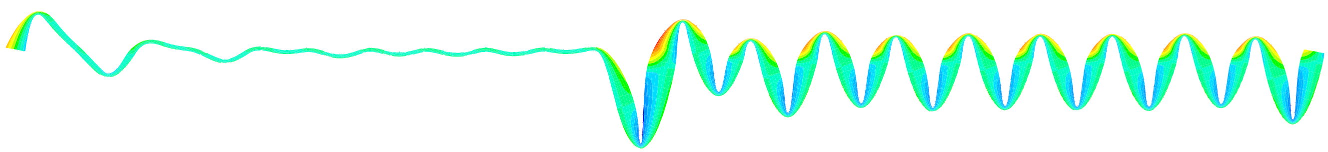
Measurement:

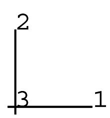
1. Maximum bulging of 3.2 mm is at 60~65% of the roll pitch from the upstream roll.
2. There is a negative bulging at the vicinity of the supporting rolls.
3. The ratio between negative bulging and positive bulging is around 0.4.

ABAQUS



Transient Behavior due to Sudden Change
of Roll Pitch: (10) 250mm >> (10) 310mm
Strain Contour Plot





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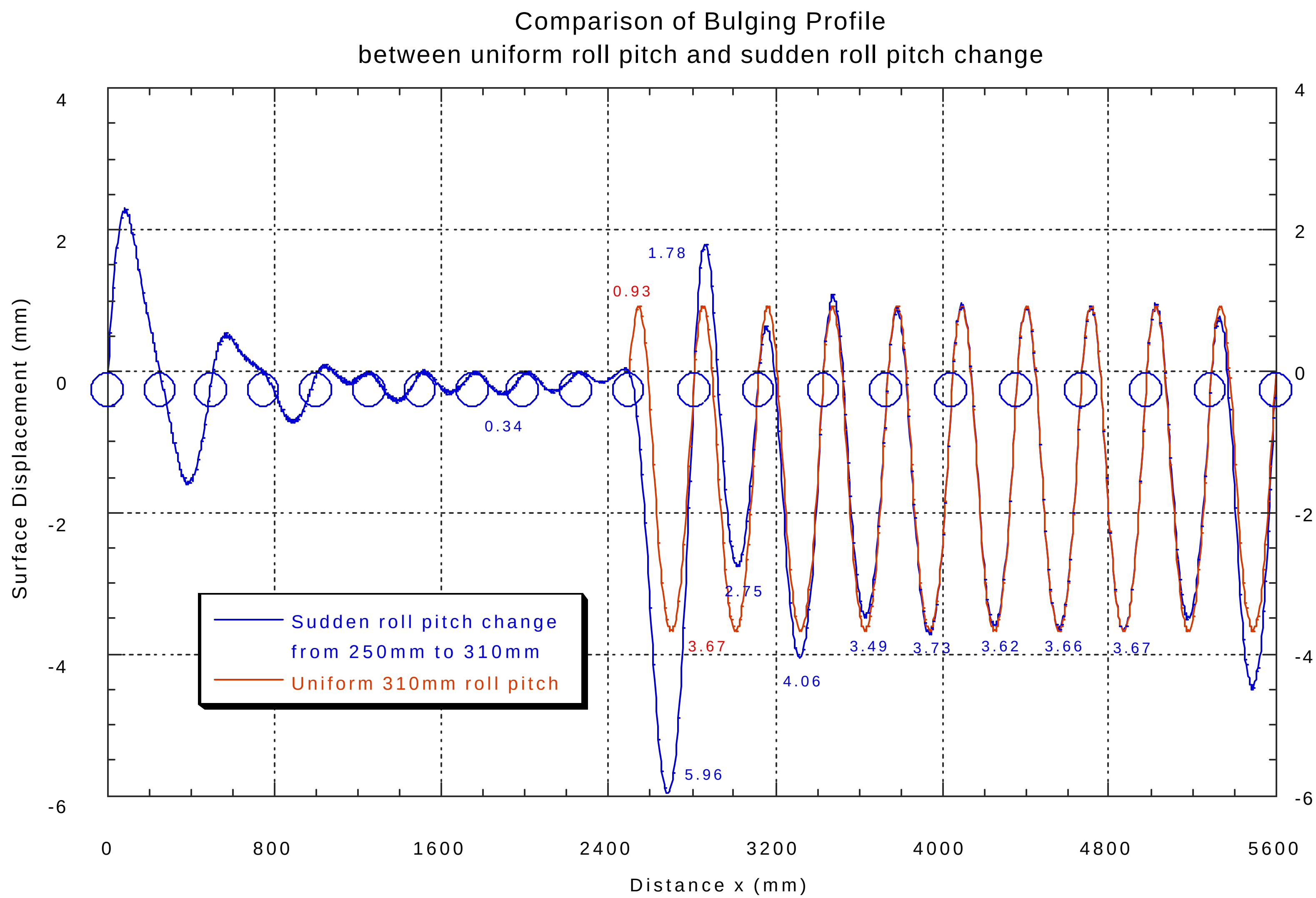
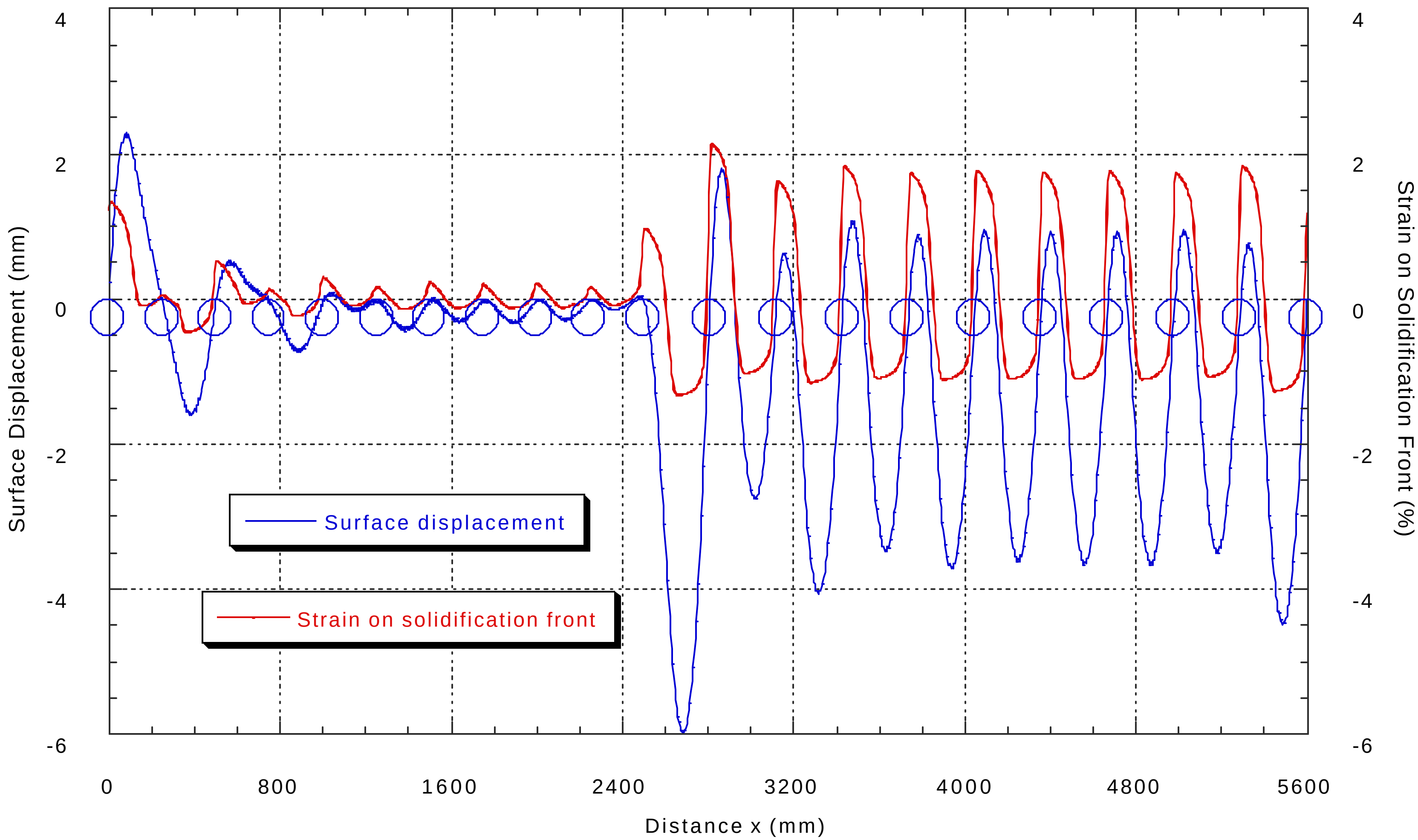
ABAQUS VERSION: 5.8-1 DATE: 18-JAN-2000 TIME: 10:32:46



Comparison of Bulging Profile
between uniform roll pitch and sudden roll pitch change
Surface Displacement (mm)
Distance x (mm)
4
2
0
-2
-4
-6
0
800
1600
2400
3200
4000
4800
5600
1.78
0.93
0.34
2.75
3.67
4.06
5.96
3.49
3.73
3.62
3.66
3.67
Sudden roll pitch change
from 250mm to 310mm
Uniform 310mm roll pitch

Bulging Profile on Surface and Strain Profile on Solidification Front



Observations

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

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

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

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

- 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.

Evaluation of Empirical Bulging Prediction Equations

- Okamura Equation (based on FEM simulations):

$$d_{\max}, e_b = AF(W/L)D^j P^k L^l T_{surf}^m V_c^n$$

Where,

$$F(W/L) = 1 - \{(pW/2L)\tanh(pW/2L) + 2\} / 2\cosh(pW/2L)$$

- Palmaers Equation (based on beam bending analysis):

$$d_{\max} = 0.4623\, C(T_{surf}) \frac{P^{1.5} L^{5.12}}{V_c^{0.22} D^{3.8}}$$

where,

$$C(T_{surf}) = \begin{cases} 0.609 \times 10^{-4} & T_{surf} = 900\,°\mathrm{C} \\ 0.725 \times 10^{-4} & T_{surf} = 1000\,°\mathrm{C} \\ 0.929 \times 10^{-4} & T_{surf} = 1100\,°\mathrm{C} \end{cases}$$

- Lamant Equation (based on beam bending analysis):

$$d_{\max} = 7.4088 \times 10^{-14} \exp(0.003866\,(T_{surf} + 273)) \frac{L^{7.16} H^{2.18}}{V_c^{0.4} D^{5.47}}$$

Comparison of Different Models

	Wunnenberg case (860mm)	Sumitomo case (310mm)	Mold exit case (165mm)
Okamura Equation	1.4985	0.4680	0.0012
Palmaers Equation	10.2025	3.5596 *	0.0332
Lamant Equation	9.0123	3.8384	0.0033
Our Model	10.61	3.67	0.02
Measurement	5~7	3.2	N/A

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

Conclusion:

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

Limitation and 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