Bulging between Rolls in Continuously-cast Slabs

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September 25, 2000

Acknowledgments

Allegheny Ludlum Corp.

AK Steel

Columbus Stainless Steel

Inland Steel

LTV Steel

Stollberg, Inc.

National Center for Supercomputing Applications
(NCSA)

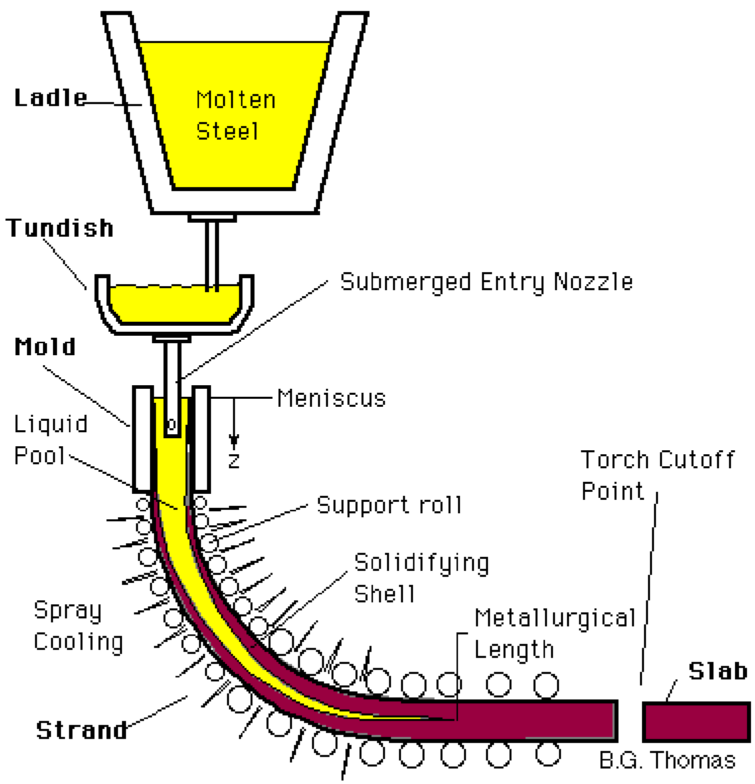
Outline

- 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

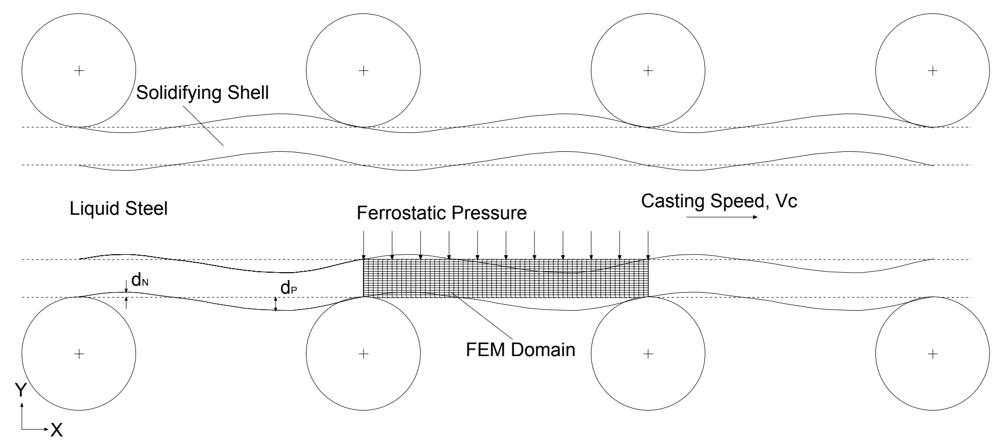
- ***Bulging*** of continuously cast steel slabs between supporting rolls is caused by internal ferrostatic pressure acting on the solidifying strand shell due to the weight of liquid steel and the height from the meniscus.
  - Bulging is directly responsible for internal cracks, centerline segregation,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

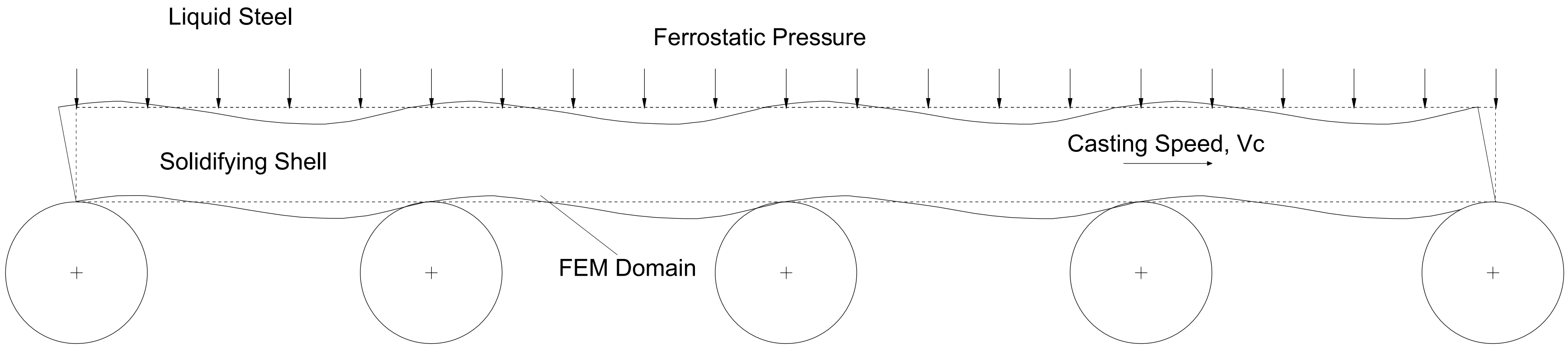
Key Phenomena

- 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

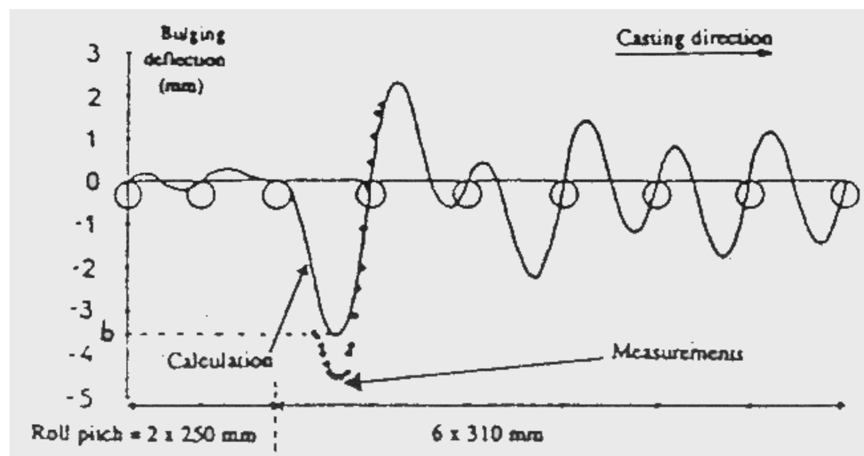
Define the Problem



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. What is the effect of roll misalignment on bulging?
3. Reproduce the simulation done by Gancarz, Lamant, et al. Is their simulation correct?



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

  $T_{Liquidus}$ = 1500 $°C$

  $T_{Surface}$ = 1000 $°C$

  Liquid steel density = 7000 kg/m^3

  Distance from meniscus = 3.9 m

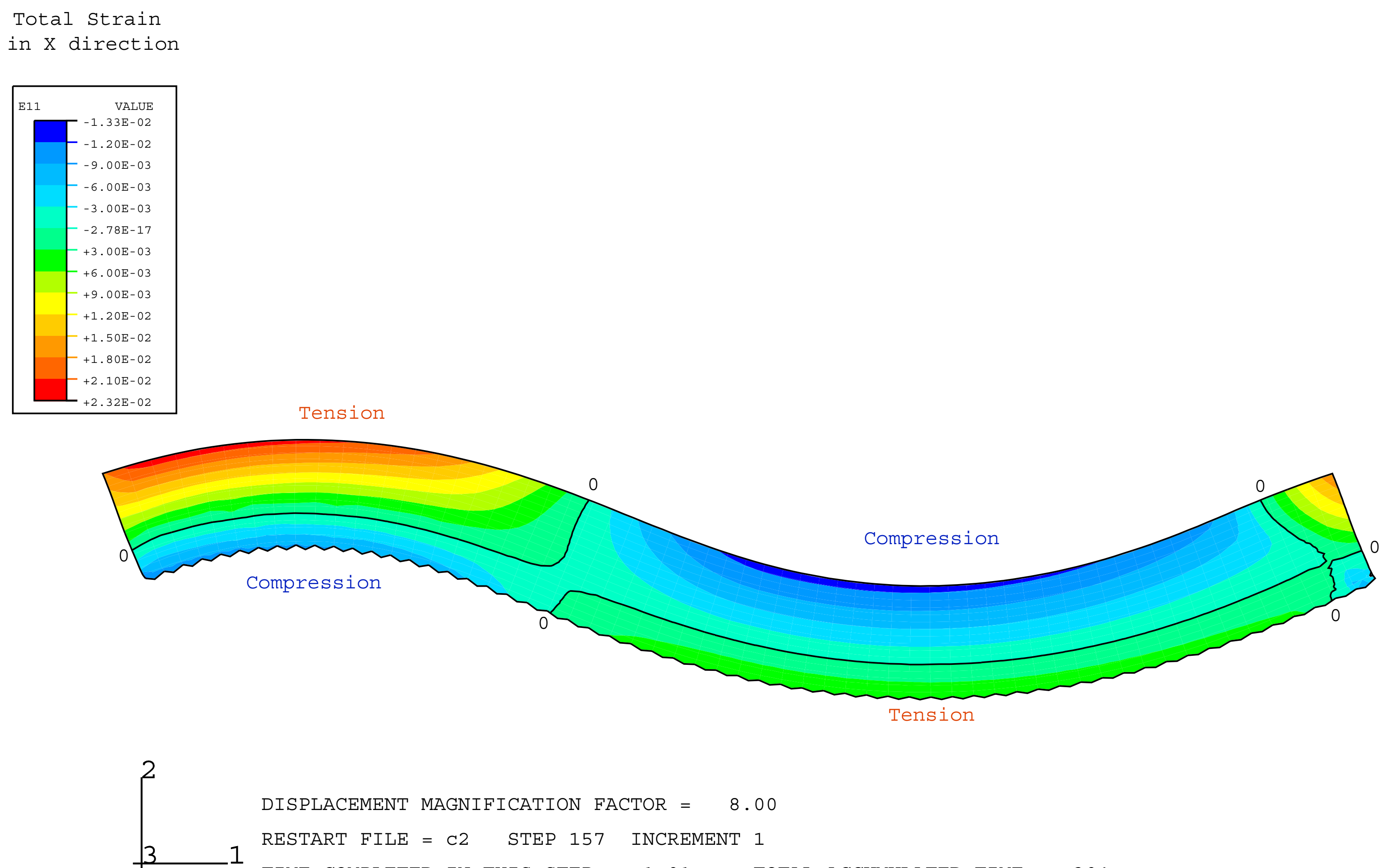
  Ferrostatic pressure = 0.26 MPa

  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)

Strain contour plot for a typical single roll pitch model



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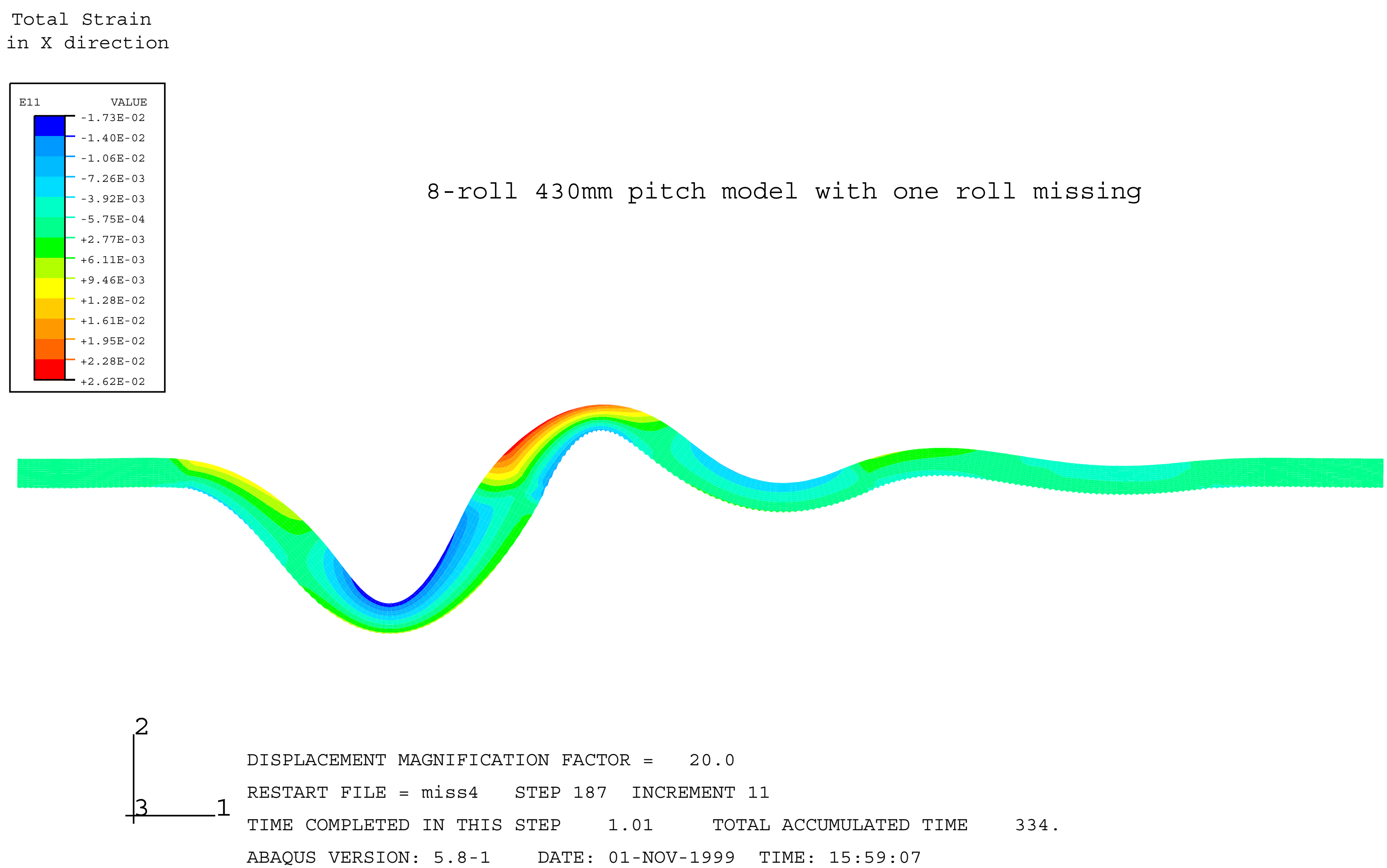
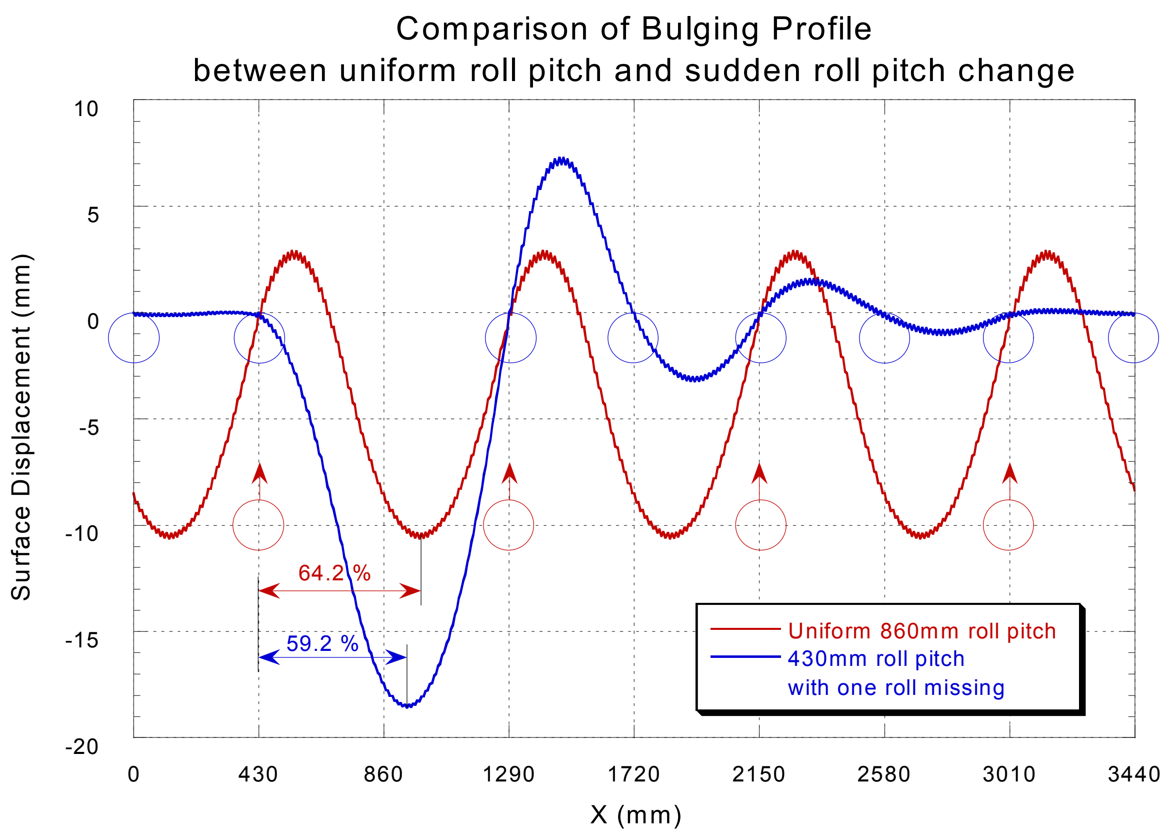
Strain contour plot for an 8-roll 430mm pitch model with one roll missing

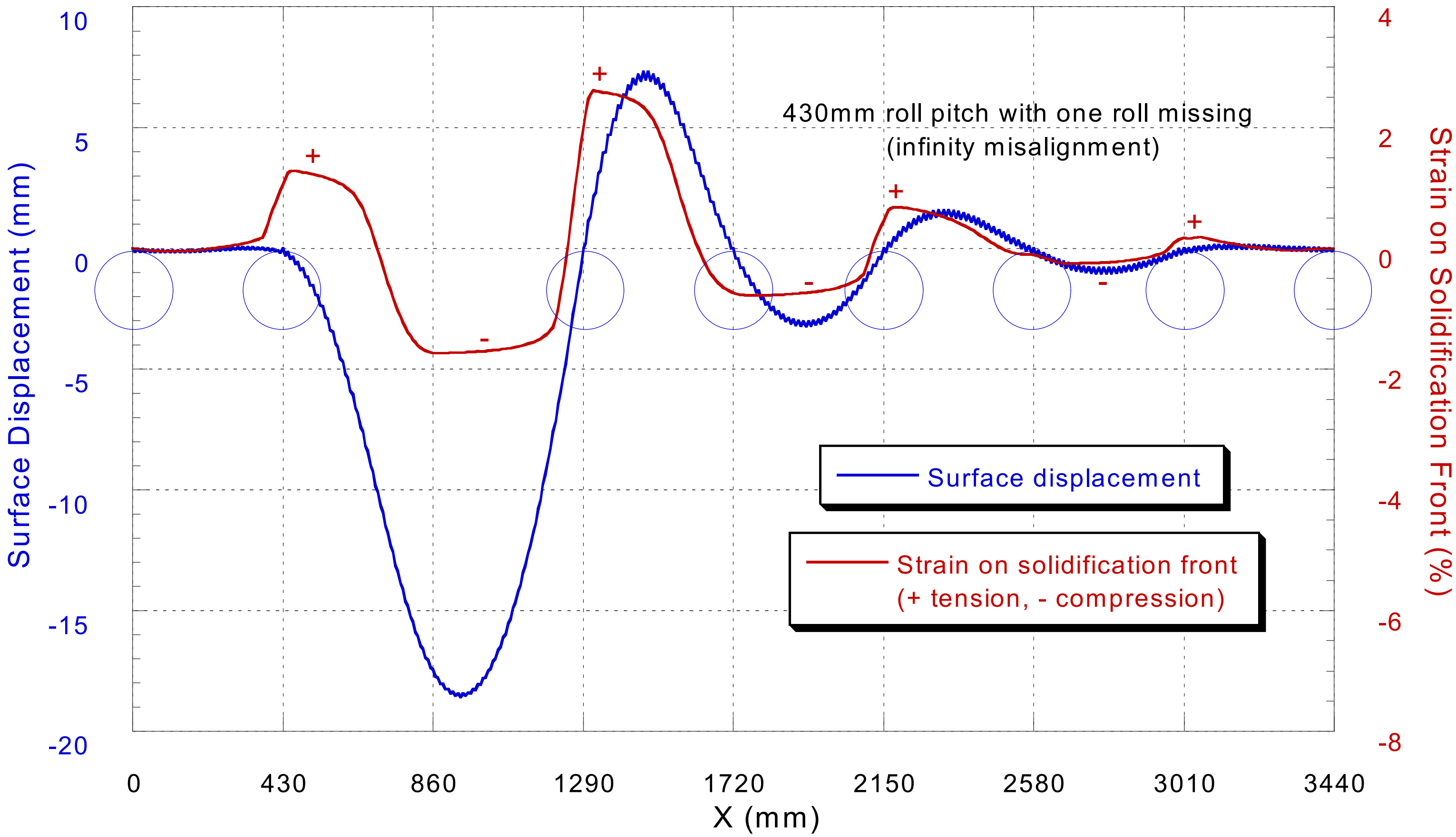




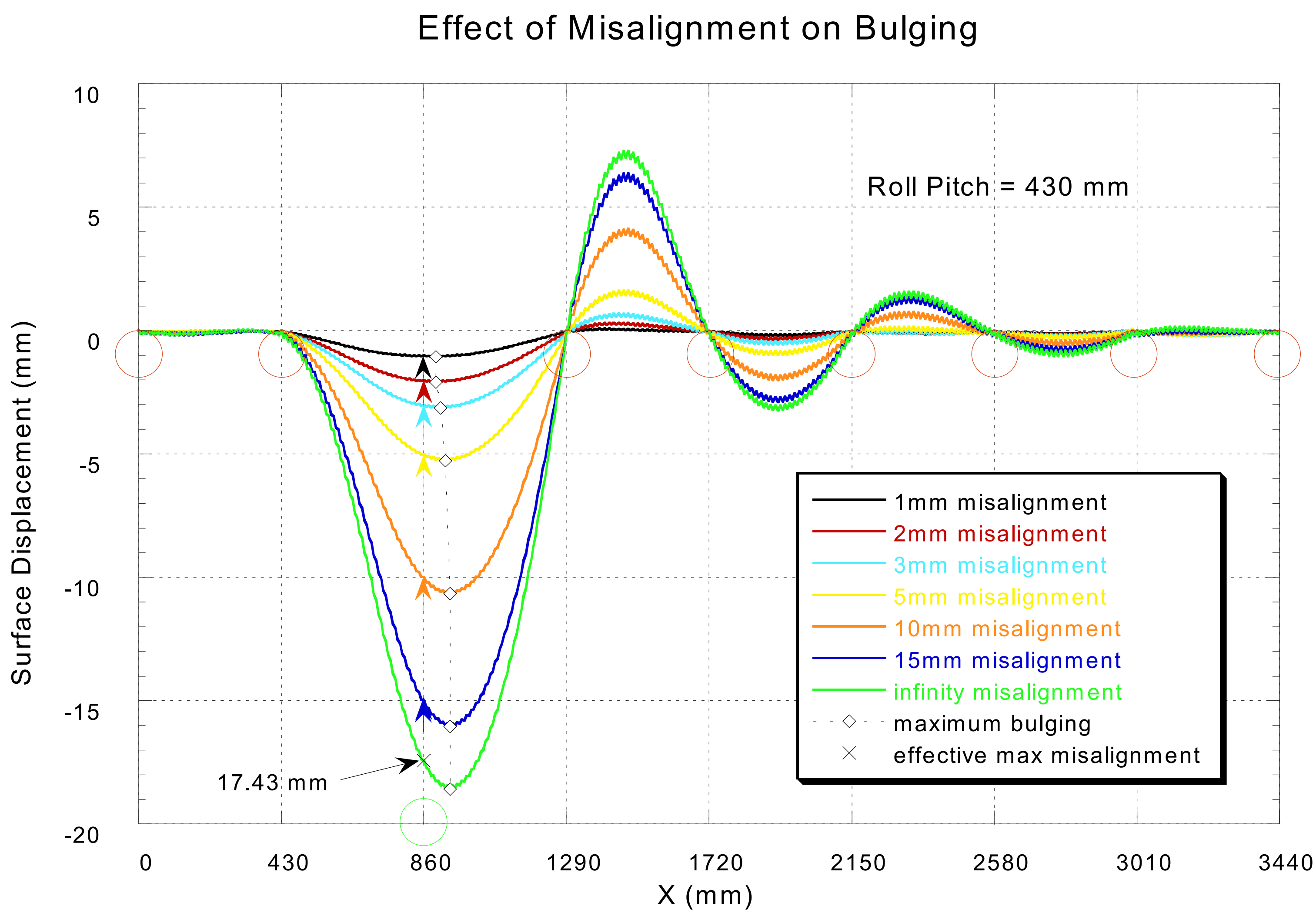
	Uniform 860mm roll pitch	430mm roll pitch with one roll missing	Difference
Maximum bulge	10.61 mm	18.57 mm	75 %
Negative bulge	2.90 mm	7.30 mm	152 %
Max strain on sol. front	2.32 %	2.62 %	12.9 %

- 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.

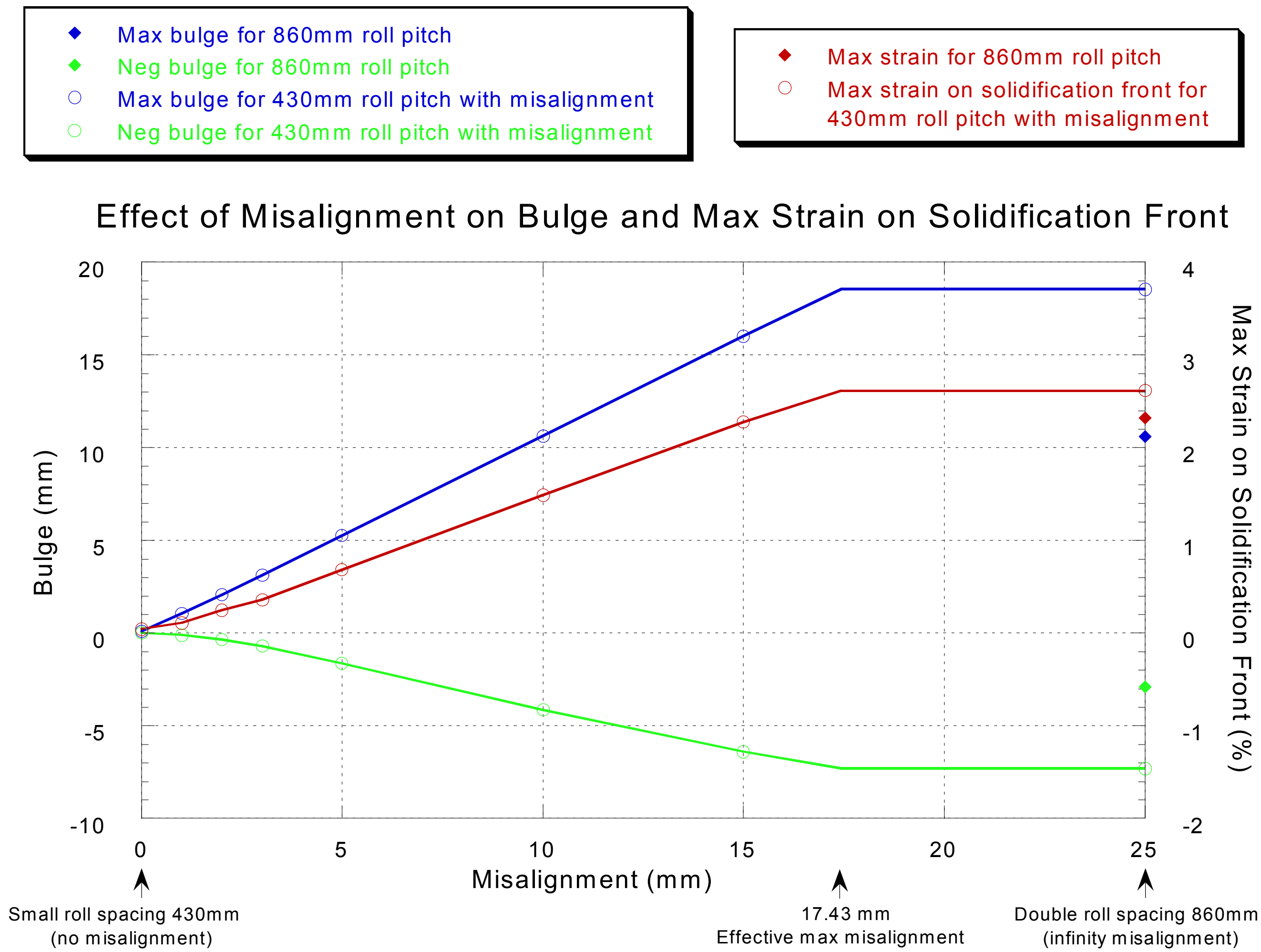
Bulging Profile on Surface and Strain Profile on Solidification Front



- 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.



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.

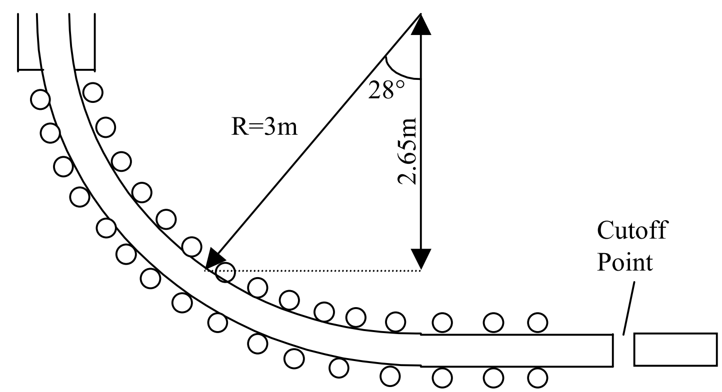
Effect of Misalignment on Bulging

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

Sumitomo Conditions

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
Shell Thickness (D) = 23.17 mm
Height from Meniscus (H) = 2.65 m
Ferrostatic Pressure = 0.18 MPa
Surface Temperature = 1220 ^oC



=> Distance from Meniscus = 3.25 m

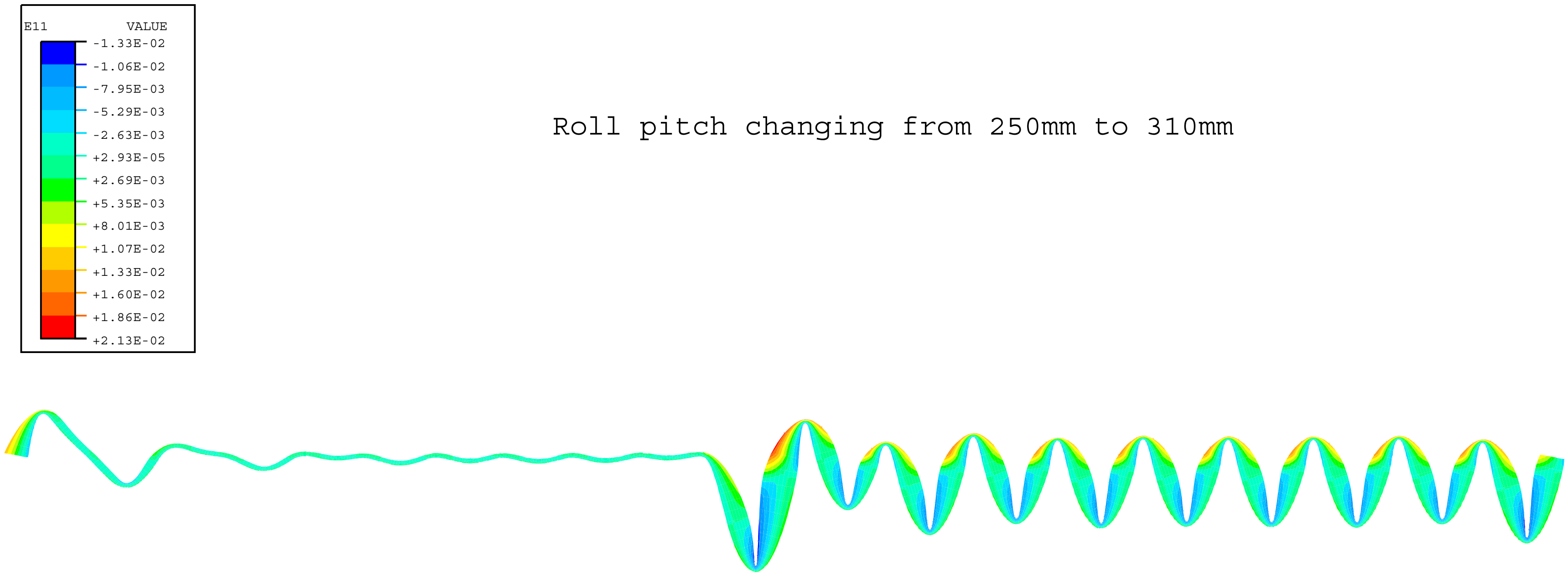
# of rolls $= \frac{3.25 - 0.7}{0.31} \approx 8$, the point of interest is around 8-9 rolls down the mold.

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



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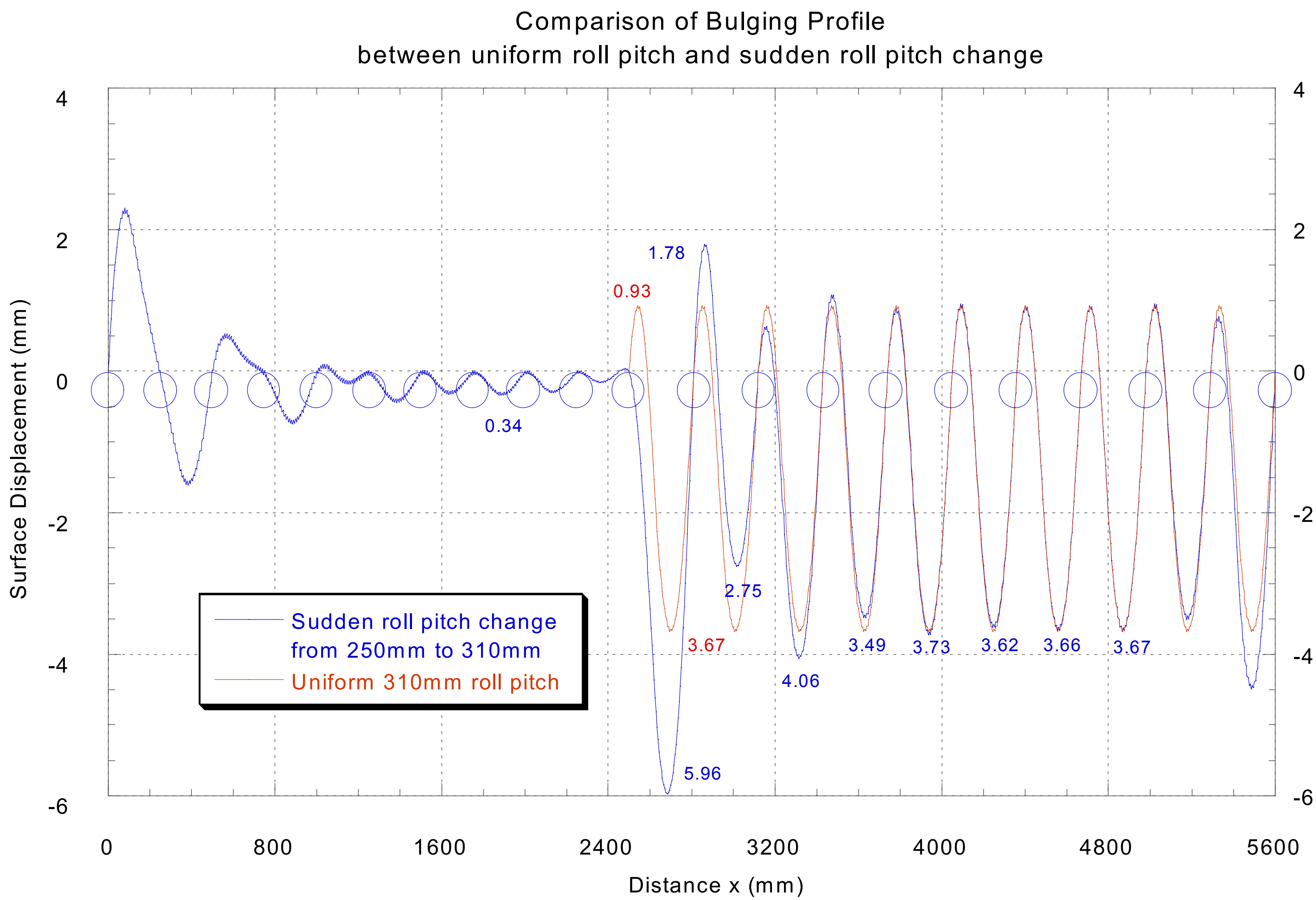
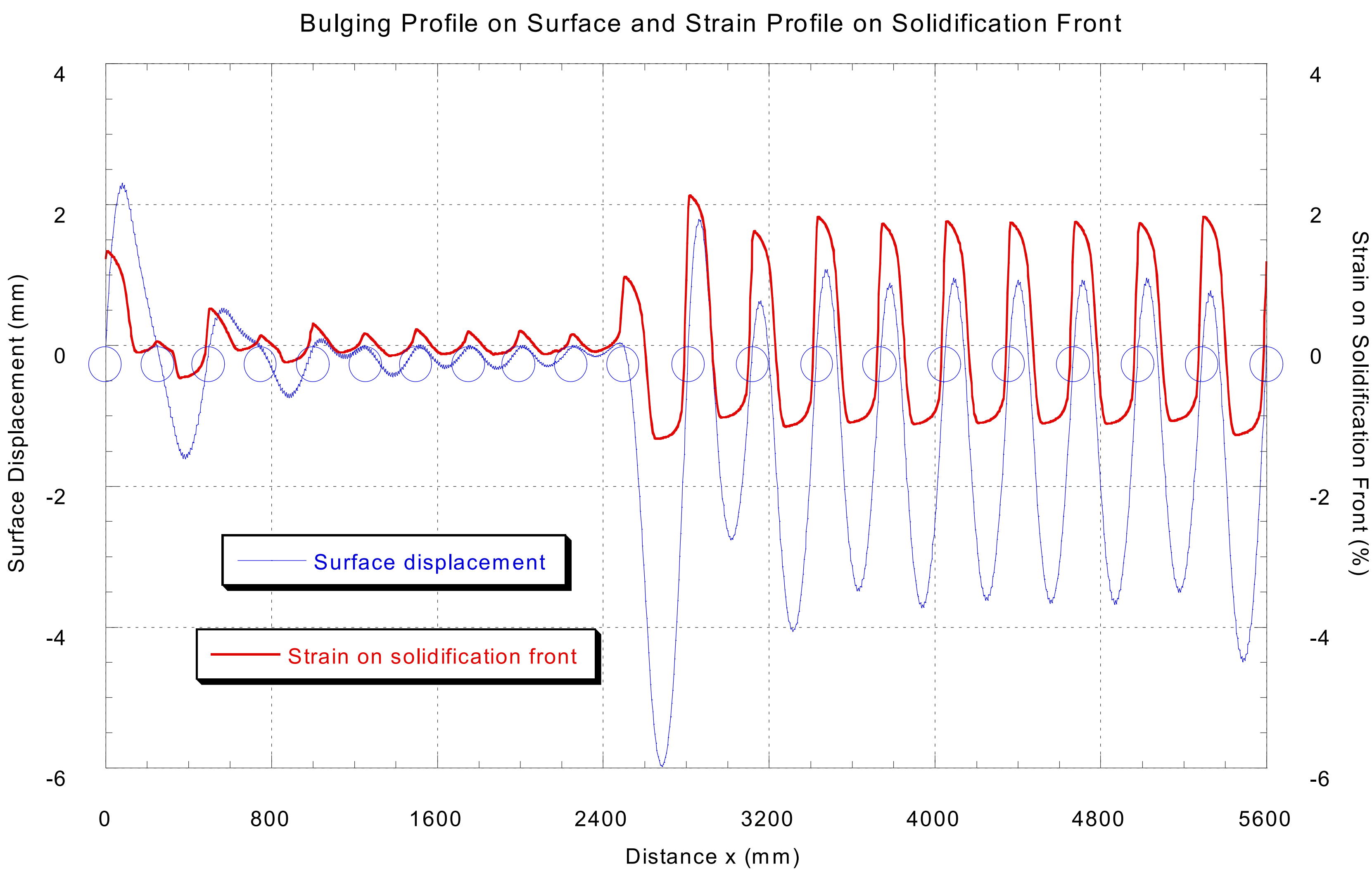

Comparison of Bulging Profile
between uniform roll pitch and sudden roll pitch change
Surface Displacement (mm)
Distance x (mm)
4
2
0
-2
-4
-6
0
800
1600
2400
3200
4000
4800
5600
1.78
0.93
0.34
2.75
3.67
4.06
3.49
3.73
3.62
3.66
3.67
5.96
Sudden roll pitch change
from 250mm to 310mm
Uniform 310mm roll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


Bulging Profile on Surface and Strain Profile on Solidification Front
Surface Displacement (mm)
Strain on Solidification Front (%)
Distance x (mm)
Surface displacement
Strain on solidification front
4
2
0
-2
-4
-6
0
800
1600
2400
3200
4000
4800
5600

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%

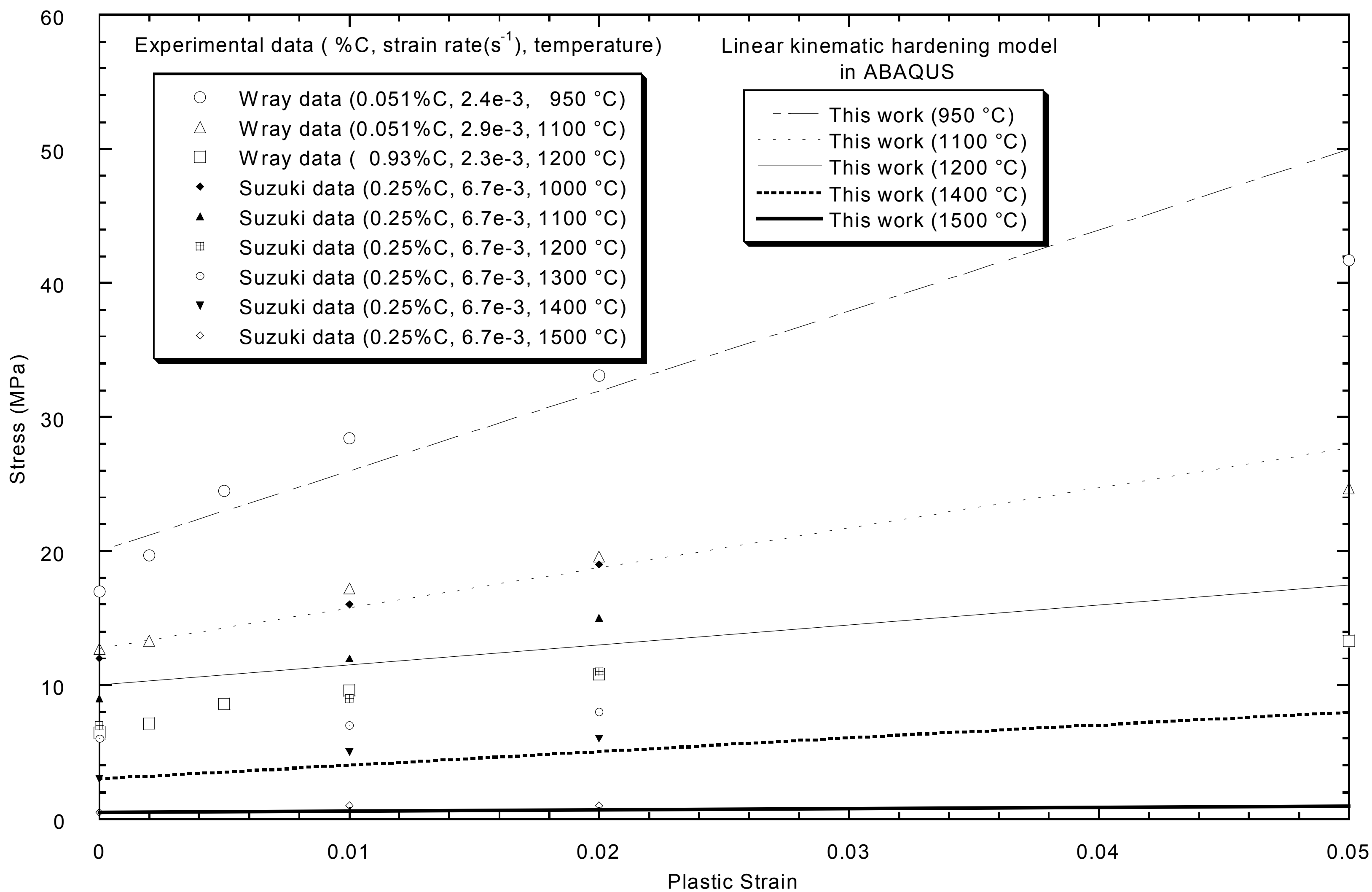
* Surface temperature changed from 1220 ^{o}C to 1000 ^{o}C to account for property uncertainty.

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

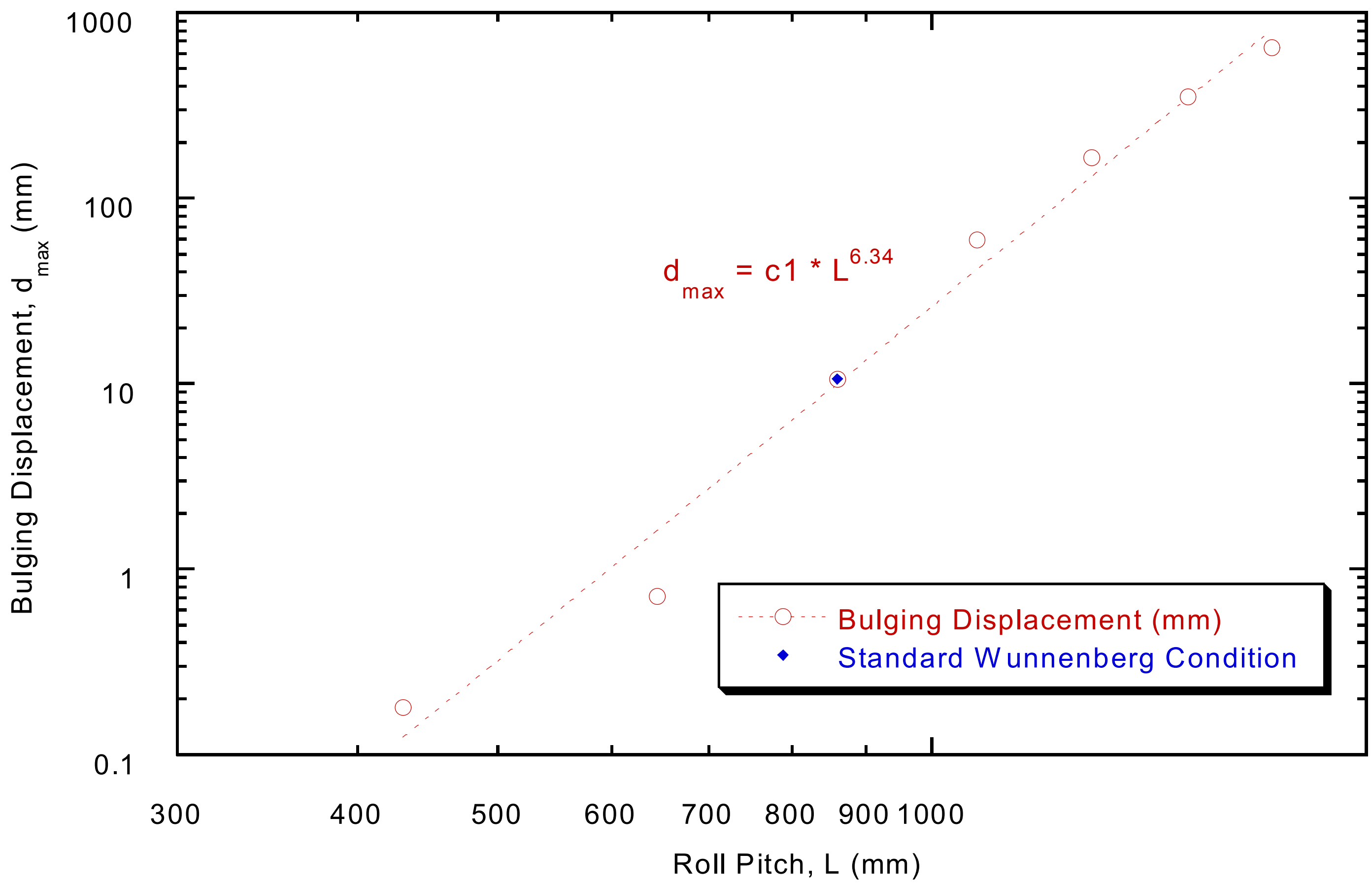
	Uniform 250mm	Sudden change from 250mm to 310mm	Uniform 310mm	Increase (sudden/uniform)
Maximum bulge	0.34 mm	5.96 mm	3.67 mm	62%
Negative bulge	0 mm	1.78 mm	0.93 mm	91%
Max strain on sol. front	0.2%	2.1%	1.75%	20%

- 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.

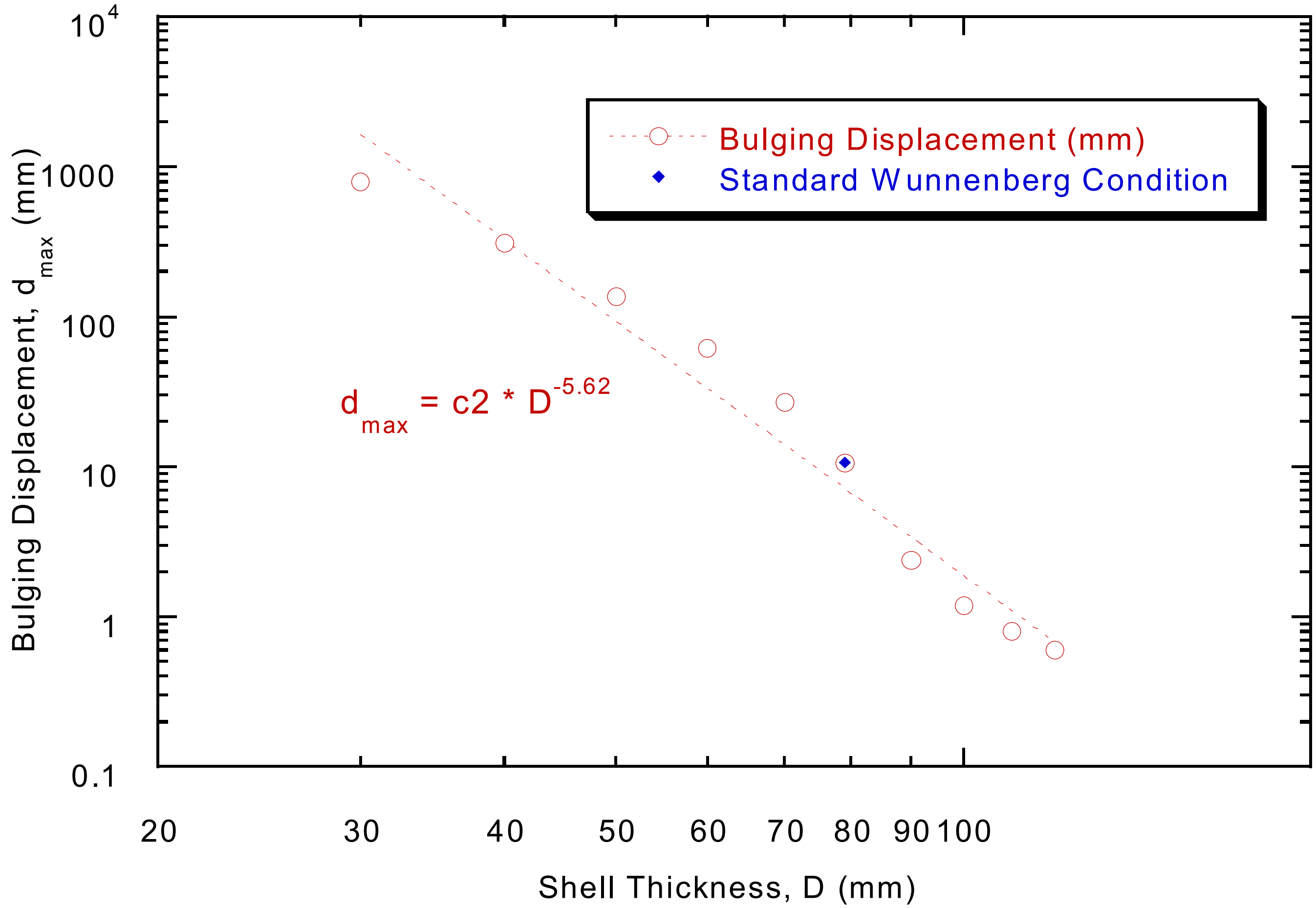
Temperature dependent stress-strain curves for plain carbon steel



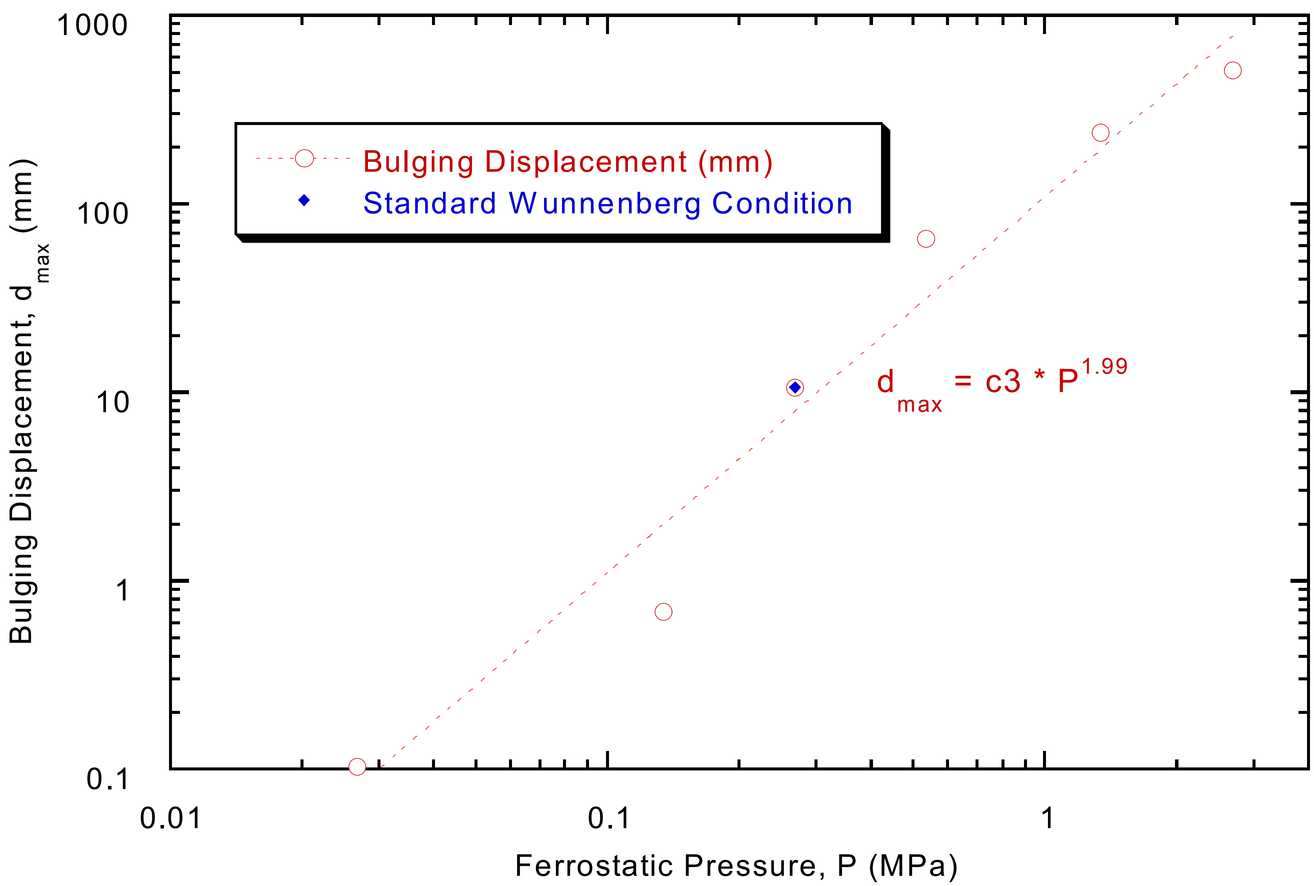
Roll Pitch Study



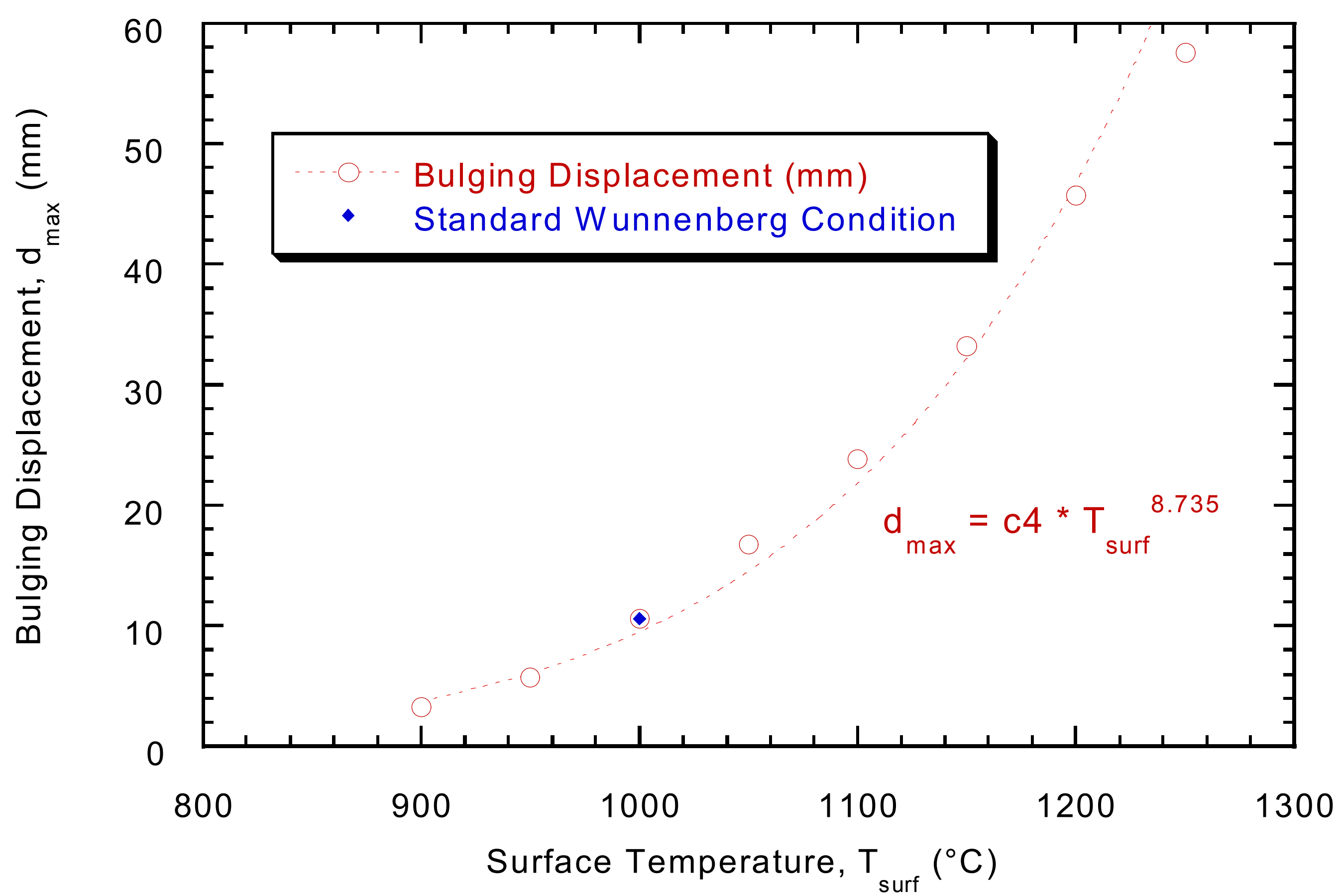
Shell Thickness Study



Ferrostatic Pressure Study



Surface Temperature Study



Bulging Prediction Equation

- 2-D shape factor from Okamura

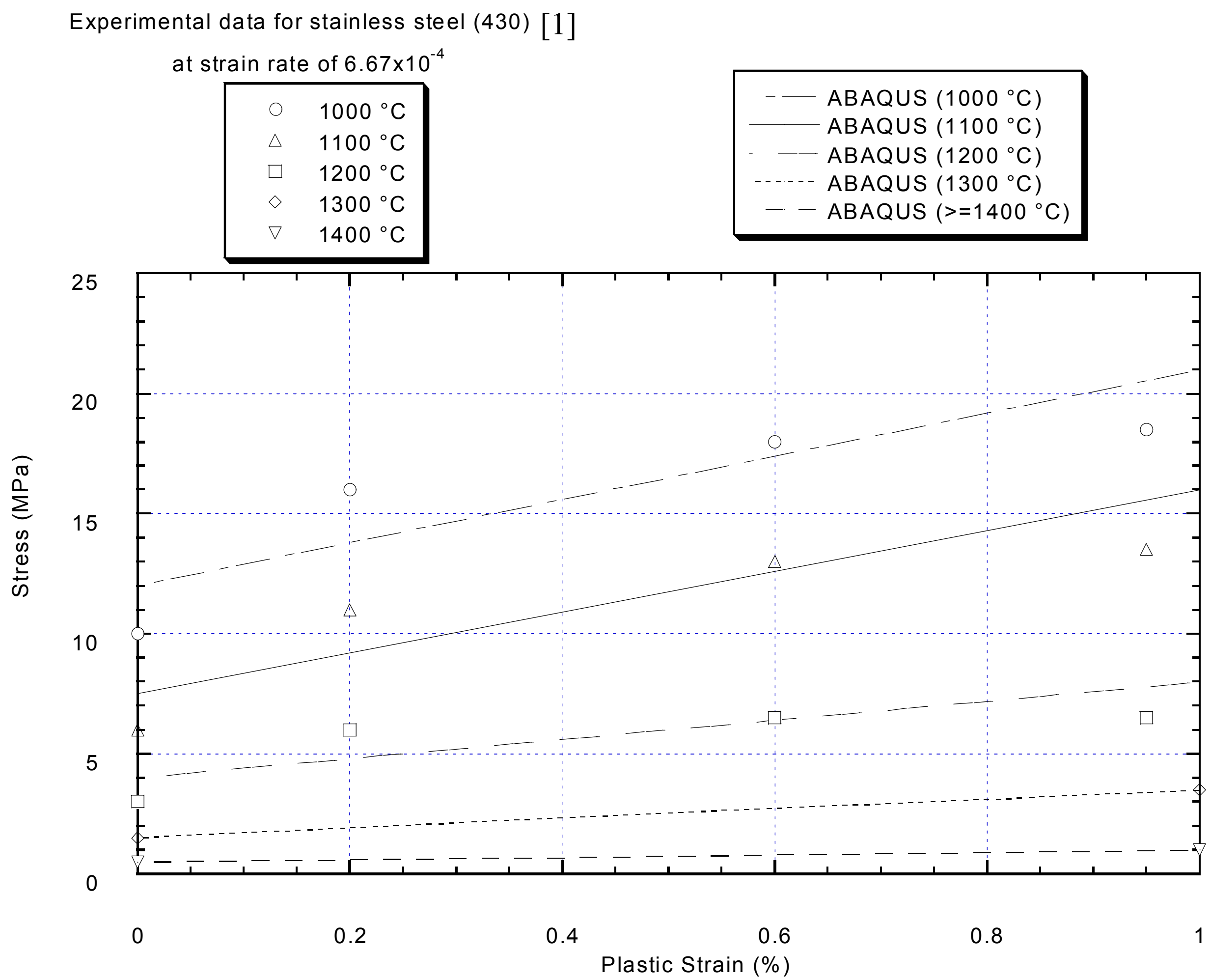
$$F(W/L) = 1 - \left\{(\pi W/2L)\tanh(\pi W/2L) + 2\right\} / 2\cosh(\pi W/2L)$$

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

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

- To be improved:
  - Casting speed
  - Material properties

Temperature dependent stress-strain curves for stainless steel



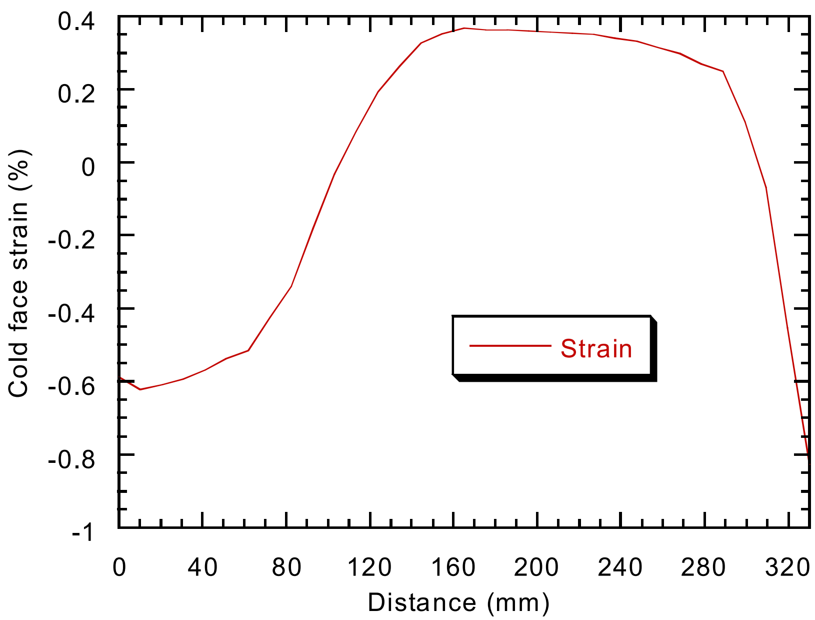
1.Kyoto University, Nippon Steel Corp. et al., "Data sheet of high temperature mechanical behavior of steel", in Metallurgy and Mechanics of Continuous Casting, ISIJ, Tokyo, Japan, 1985, pp. 343-344.

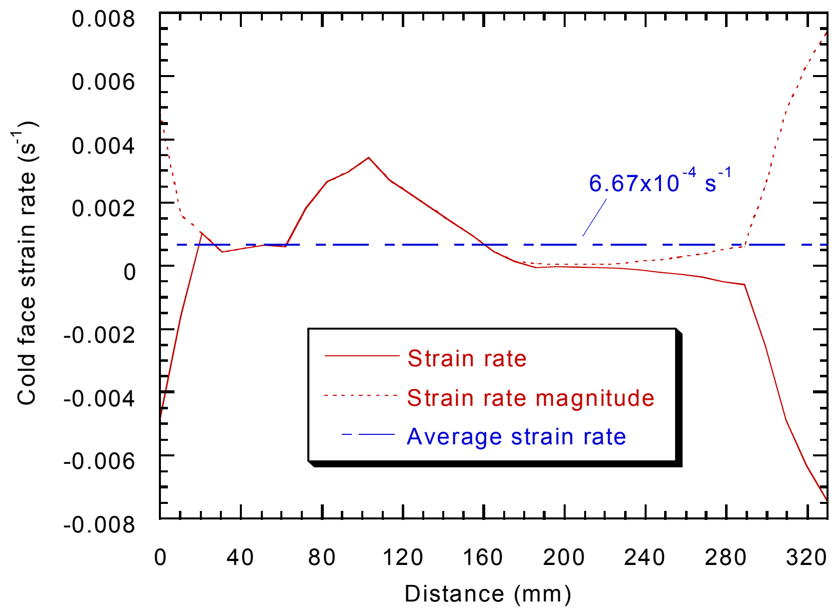
Armco Case Study

		Case 1	Case 2	Case 3
Roll pitch, L (mm)		330	165	165
Shell thickness, D (mm)		12	17	28.3
Ferrostatic pressure, P (MPa)		0.0223	0.0446	0.1235
Surface temperature, T_{surf} (^oC)		1000	1000	1000
d_{max} (mm)	Plain carbon steel	0.6548	0.0240	0.0184
	Stainless steel	8.88	0.0315	0.0287
	Our Equation	6.8256	0.0474	0.0206

- 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 $6.67 \times 10^{-4}\ s^{-1}$

Evaluation of Empirical Bulging Prediction Equations

- Okamura Equation (based on FEM simulations):

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

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):

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

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)	Armco case 3 (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 Equation	6.256	3.5667 **	0.0206
Our model (raw / adjusted)	10.61 / 6.64	3.67 / 1.79 **	0.0184 / 0.0184
Measurement	5~7	3.2	N/A

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

** Surface temperature of 1000 ^{o}C is used instead of 1220 ^{o}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

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

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