Bulging between Rolls in Continuously-cast Slabs

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Accumold
Allegheny Ludlum Corp.
AK Steel
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LTV Steel
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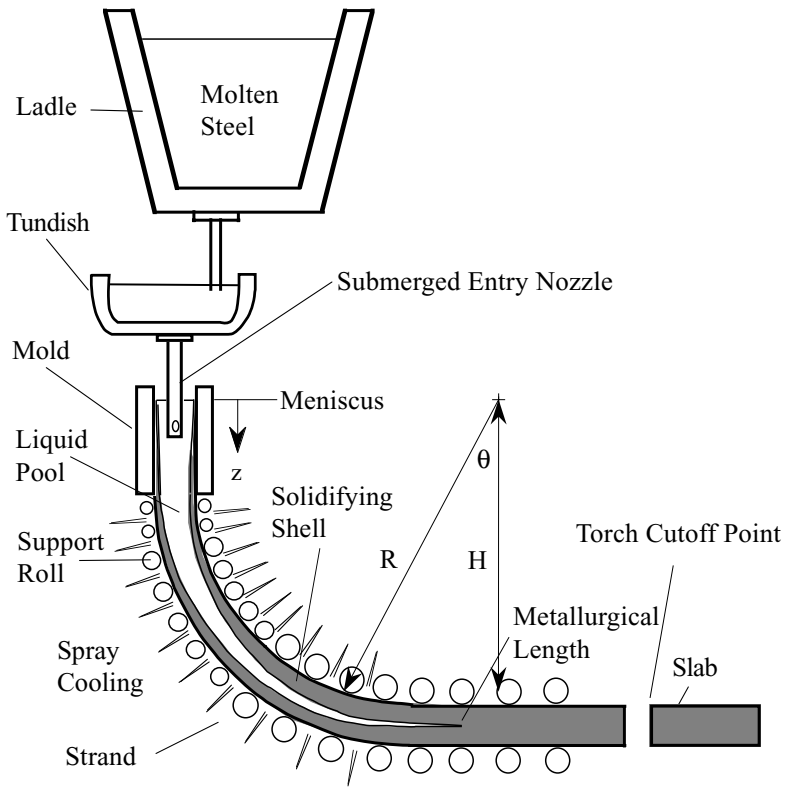
Outline

- Introduction
- Single roll pitch model
- Multiple-roll pitch model
  - Effect of roll misalignment
  - Warped roll simulation
  - Effect of sudden roll pitch change
- Parametric study
  - Bulging prediction equation
  - Equation to predict strain at solidification front
- Evaluation of empirical bulging prediction equations
- Applications

Introduction

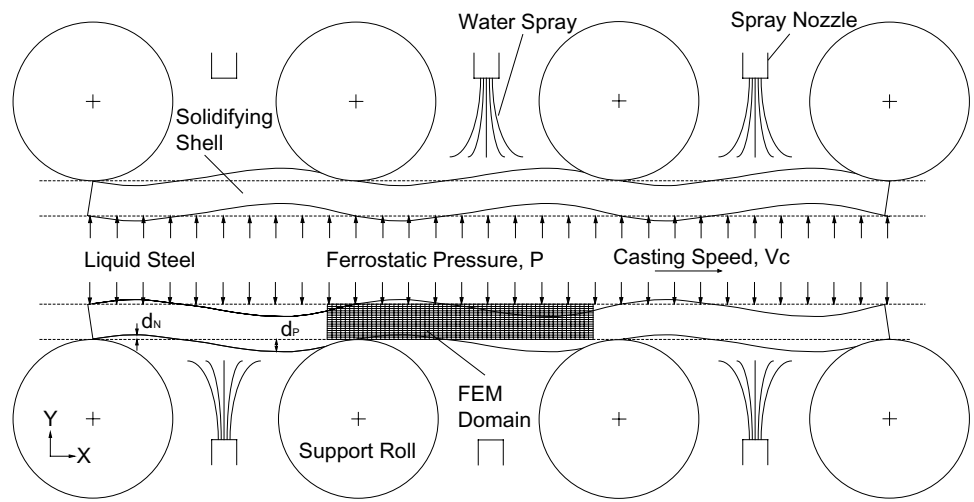
- ***Bulging*** of continuously cast steel slabs between supporting rolls is caused by internal ferrostatic pressure acting on the solidifying strand shell due to the weight of liquid steel and the height from the meniscus.
  - Bulging is directly responsible for internal cracks, centerline segregation,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

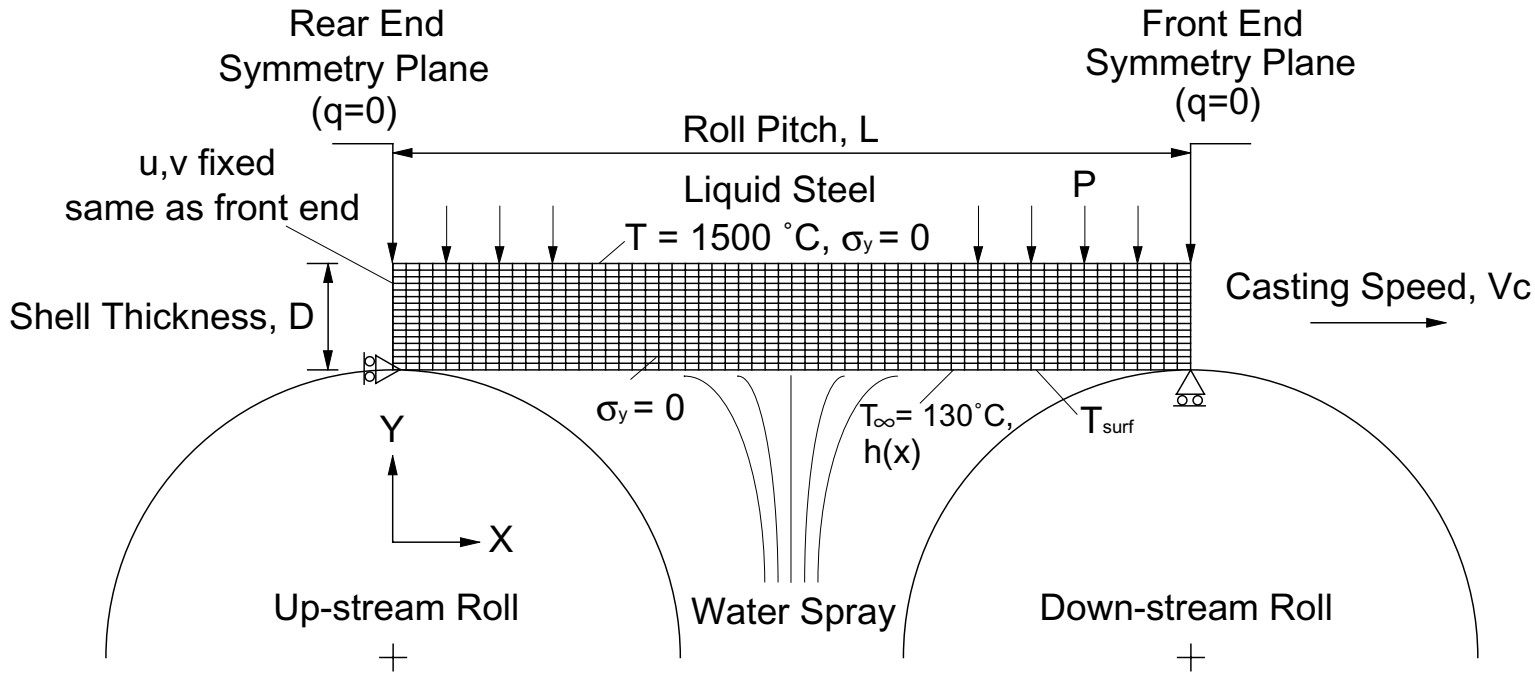
(Acknowledgement to Prof. Brian G. Thomas)



2D FEM single roll pitch model for bulging

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

Single roll pitch model



- Periodic boundary condition:

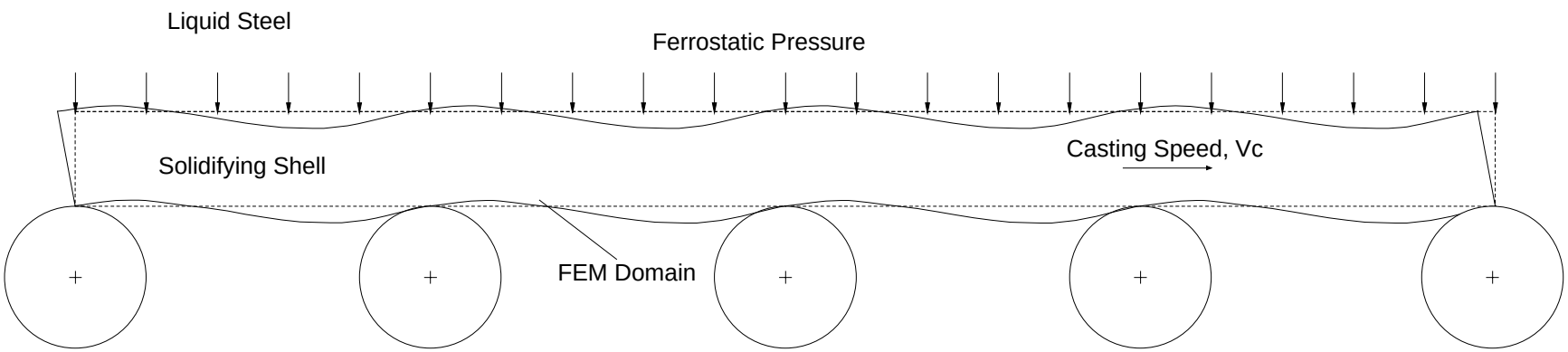
  $u_{rear\ end}$ constrained to equal $u_{front\ end}$ and $v_{rear\ end}$ constrained to equal $v_{front\ end}$

  So that the angles of the front and rear ends of the domain are the same. Thus, only a single vertical support (representing the roll, v=0) is needed to prevent rigid body motion.

Modeling methodology

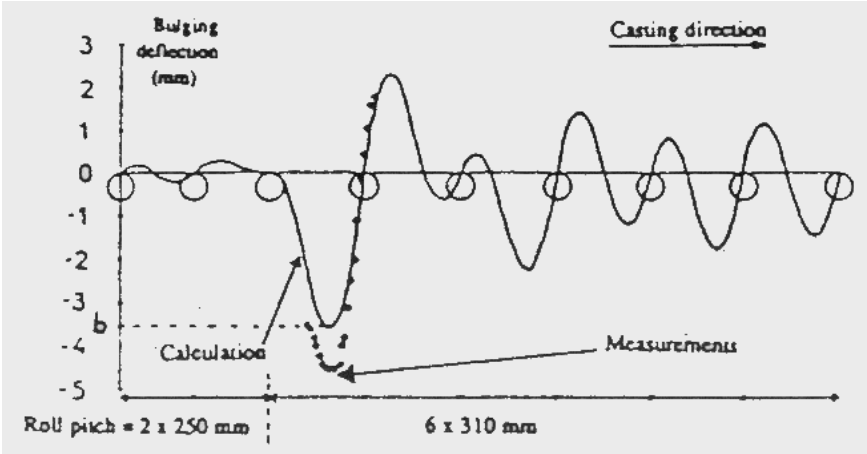
- 2-D Finite Element Method thermal stress model with Lagrangian approach is developed using commercial FEM package ABAQUS.
  - Stress analysis
  - Nonlinear problem
- Simplifying Assumptions:
  - 2-D elastic-plastic model with plane stress assumption
  - Constant solidified shell thickness
  - Uniform ferrostatic pressure along X
  - Constant temperature gradient across the shell thickness with uniform temperature profile along X

Multiple roll pitch model



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?



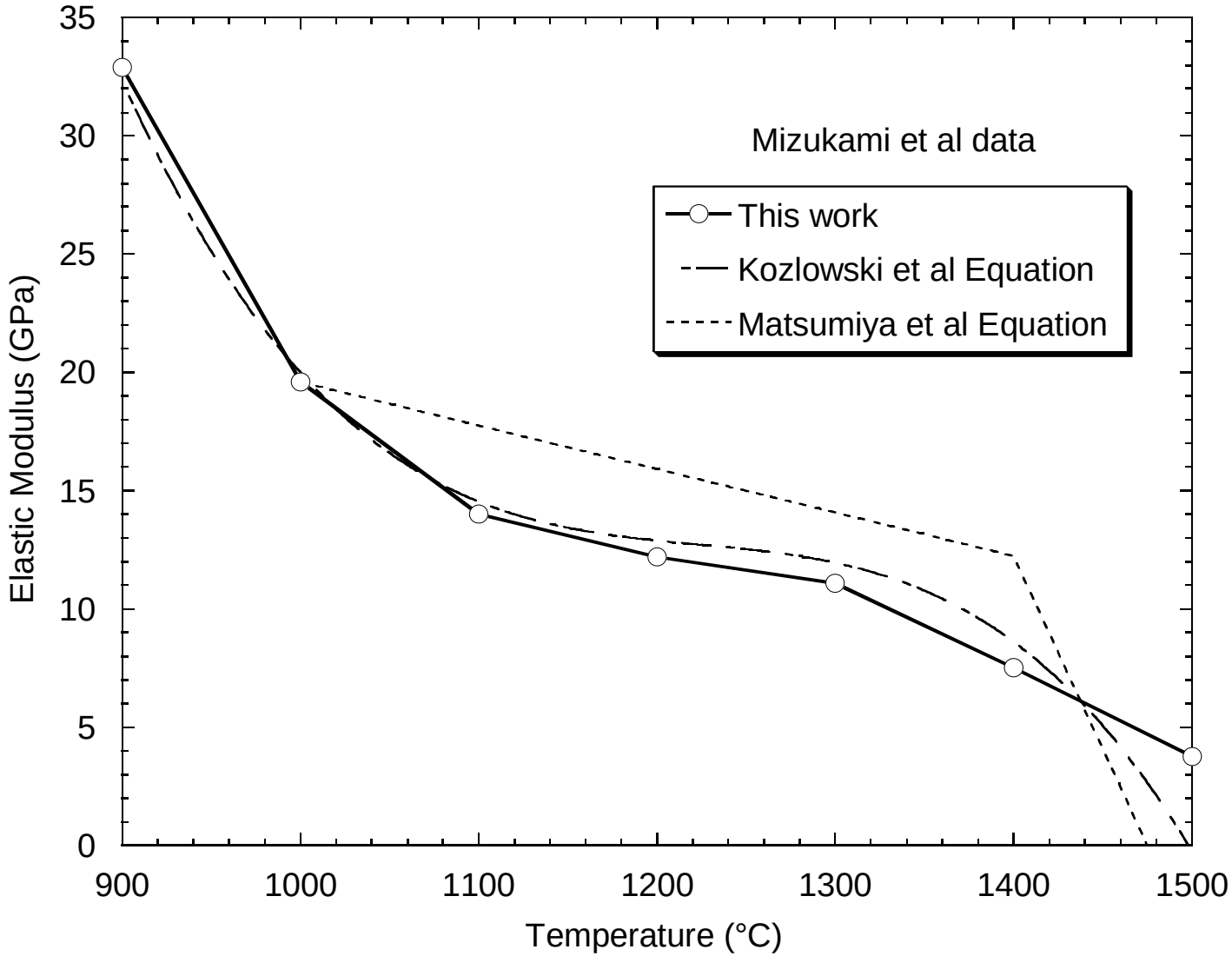
Experimental bulging profile on Sumitomo and Calculations over 9 rolls done by Gancarz, Lamant, et al.

Wunnenberg conditions and Sumitomo conditions

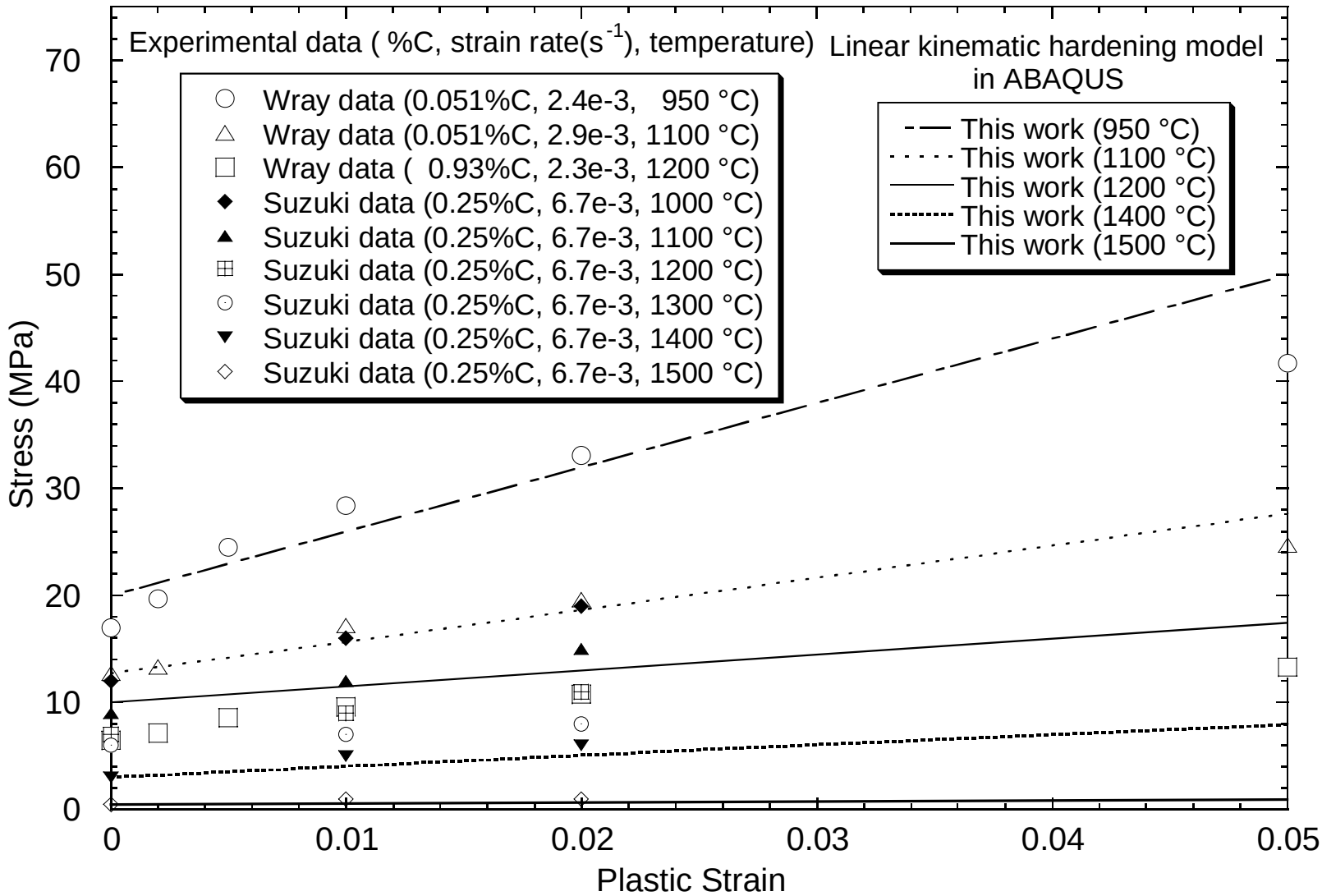
	BS pilot slat caster (Wunnenberg)	Pilot caster at Sumitomo Metals
Steel grade	X60 (C: 0.26%, Mn: 1.35%, P: 0.040%, Nb: 0.05%, V: 0.02%, Ti: 0.03%)	AISI 1518 Steel (C: 0.18%)
Caster Radius (R)	3.9 m	3 m
Slab width (W)	>1300 mm (1350 mm)	400 mm (400 x 100 mm^2 slab)
Roll pitch (L)	860 mm	310 mm
Shell thickness (D)	79 mm	23.17 mm
Surface Temperature (T_{surf})	1030 °C *	1220 °C
Casting speed (V_c)	0.85 m/min = 14.2 mm/s	1.65 m/min = 27.5 mm/s
Liquid steel density (ρ)	7000 kg/m^3	7000 kg/m^3
Height from meniscus (H)	3.9 m	2.65 m
Ferrostatic pressure (P)	0.26 MPa	0.18 MPa
Angle (θ)	0°	28°

* Given only this single surface temperature measurement, the constant average surface temperature of 1000°C is assumed for the models.

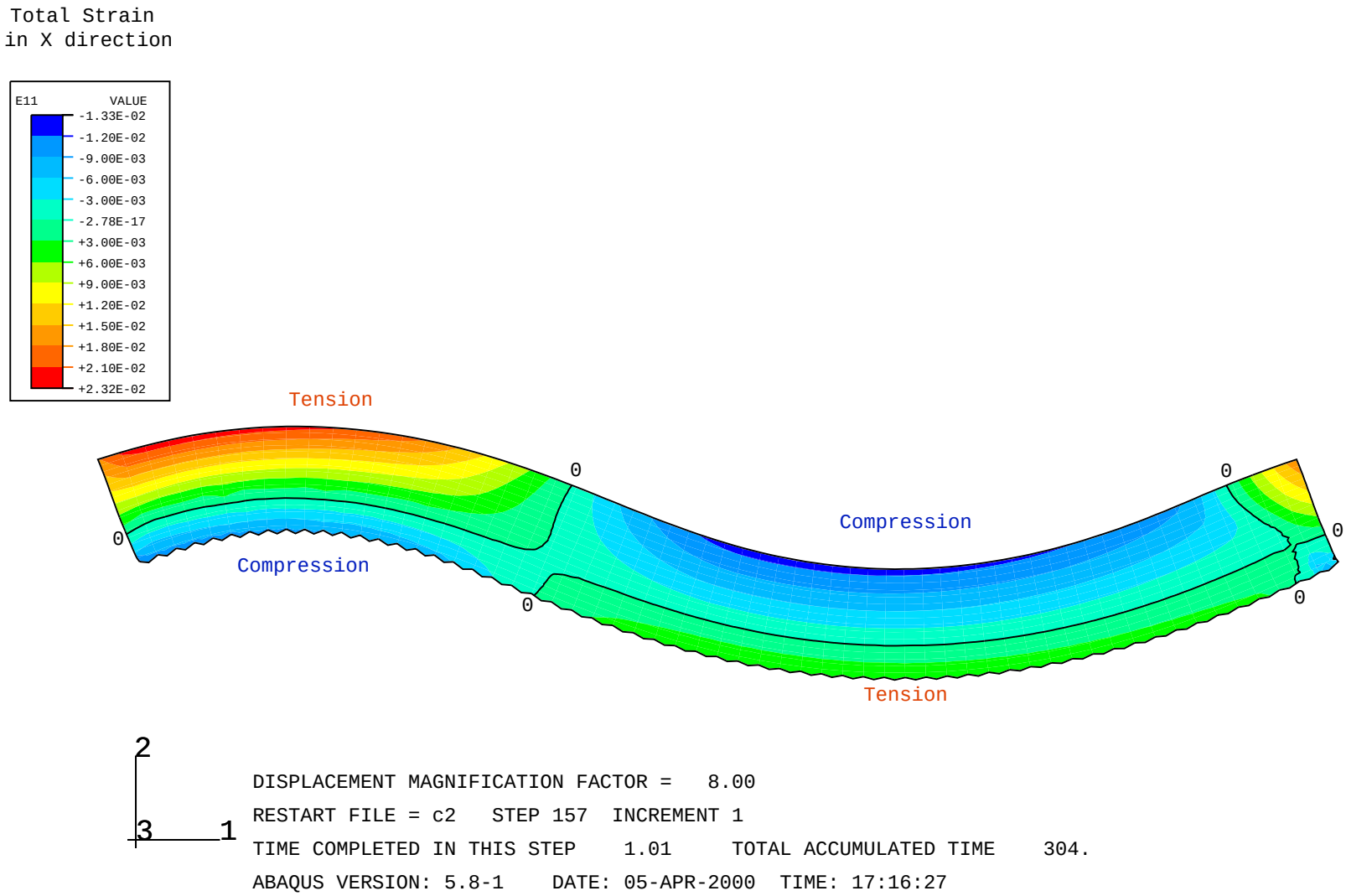
Temperature dependent elastic modulus



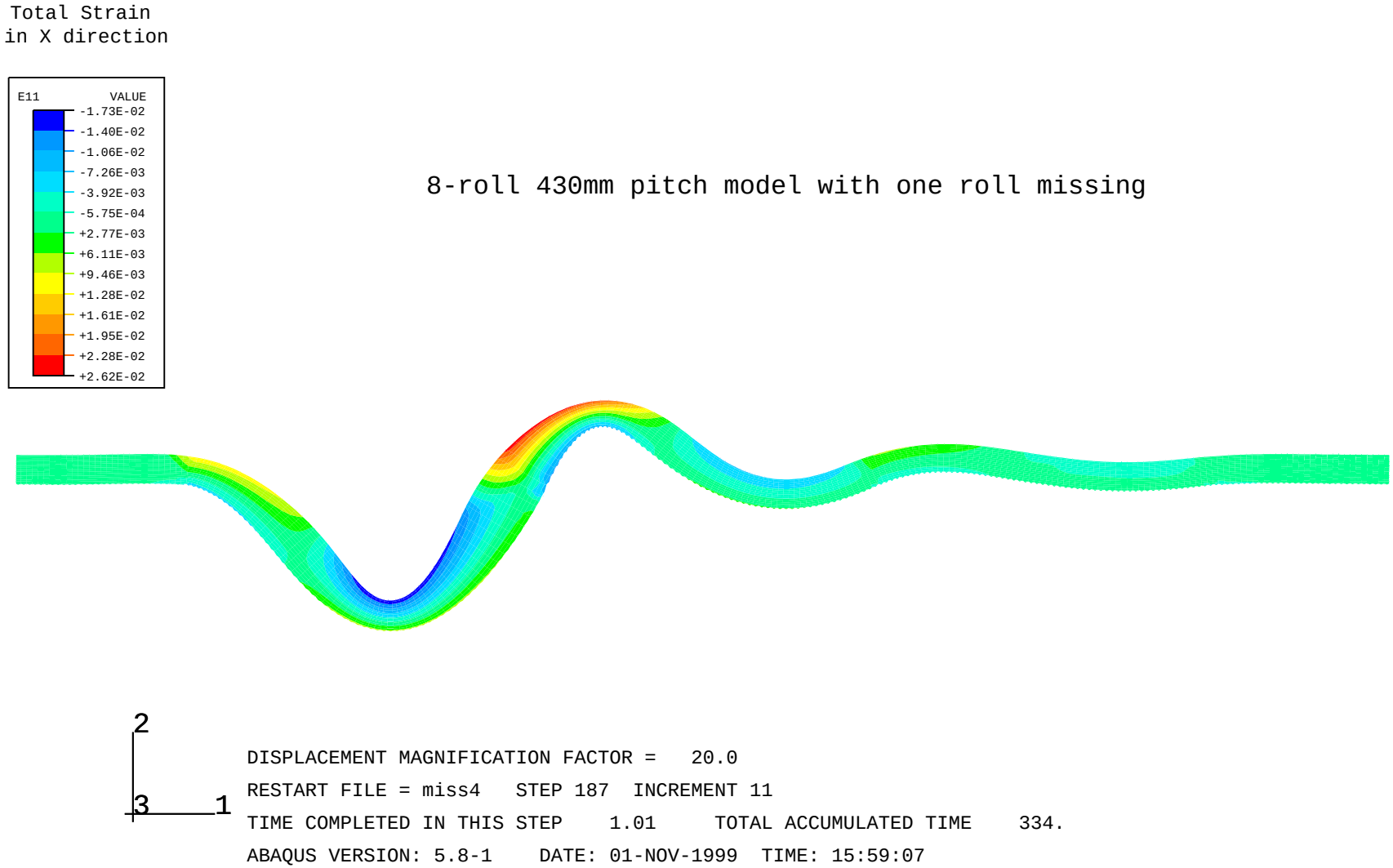
Temperature dependent stress-strain curves for plain carbon steel

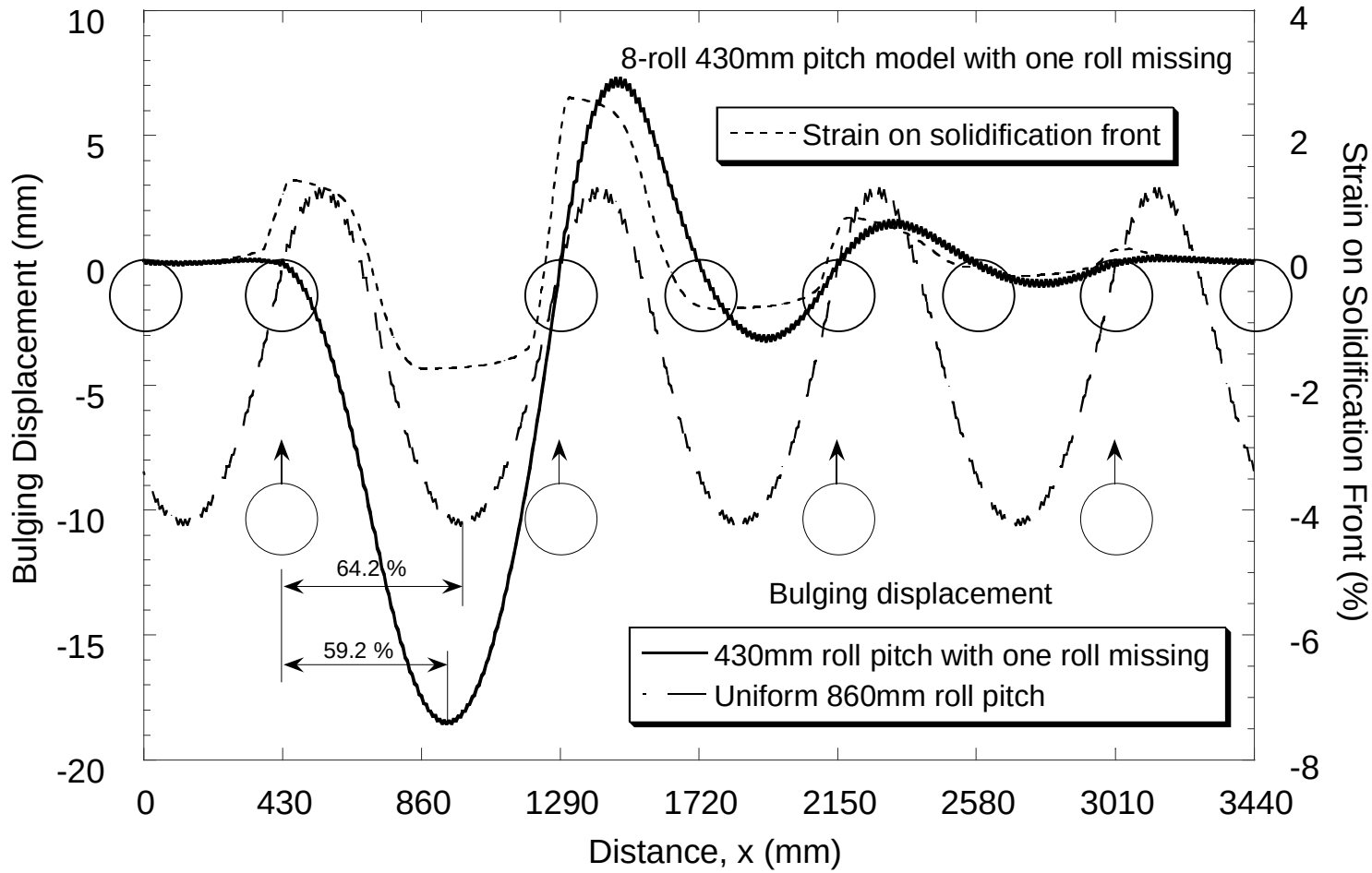


Strain contour plot for a typical single roll pitch model



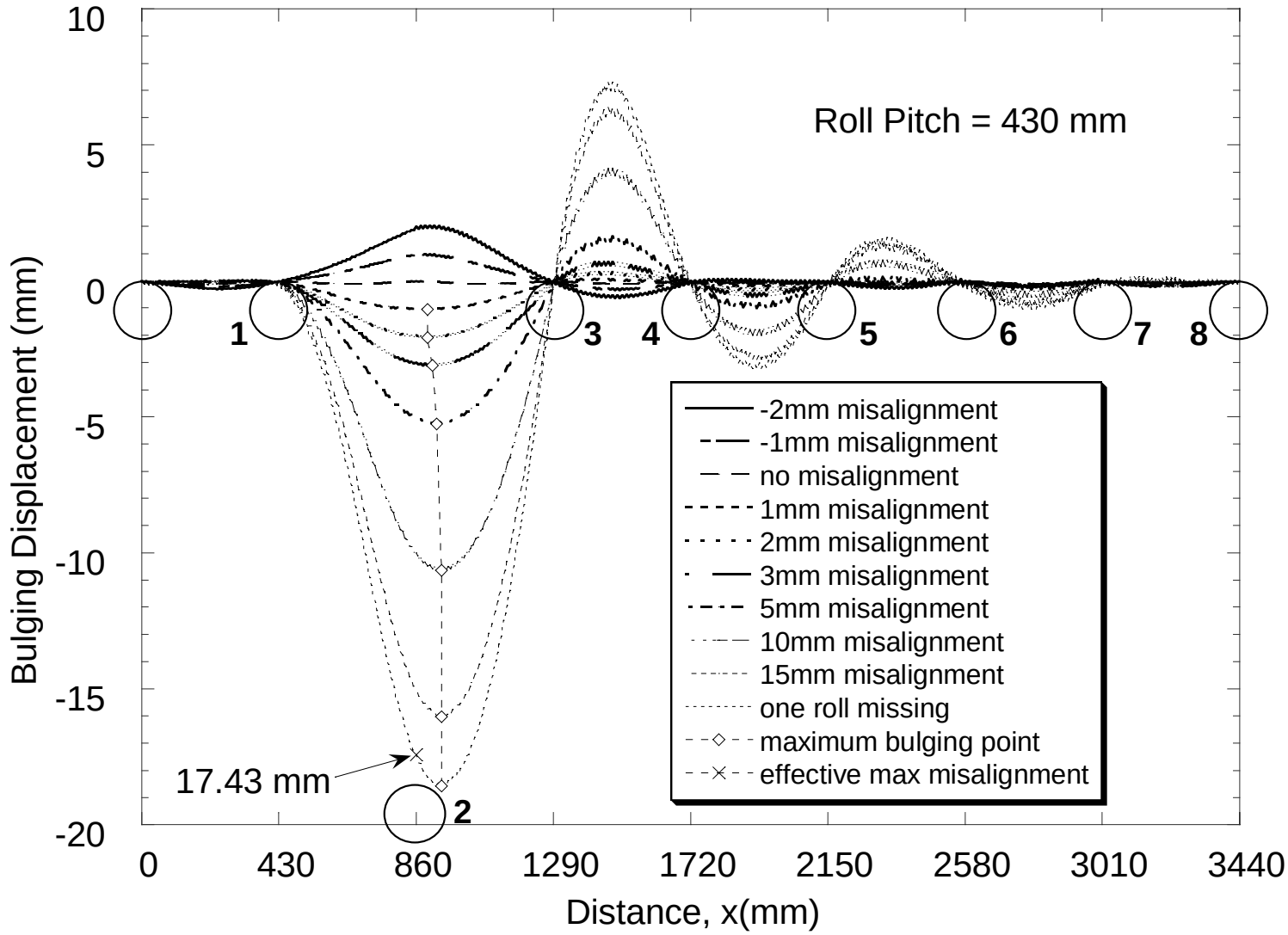
Strain contour plot for an 8-roll 430mm pitch model with one roll missing





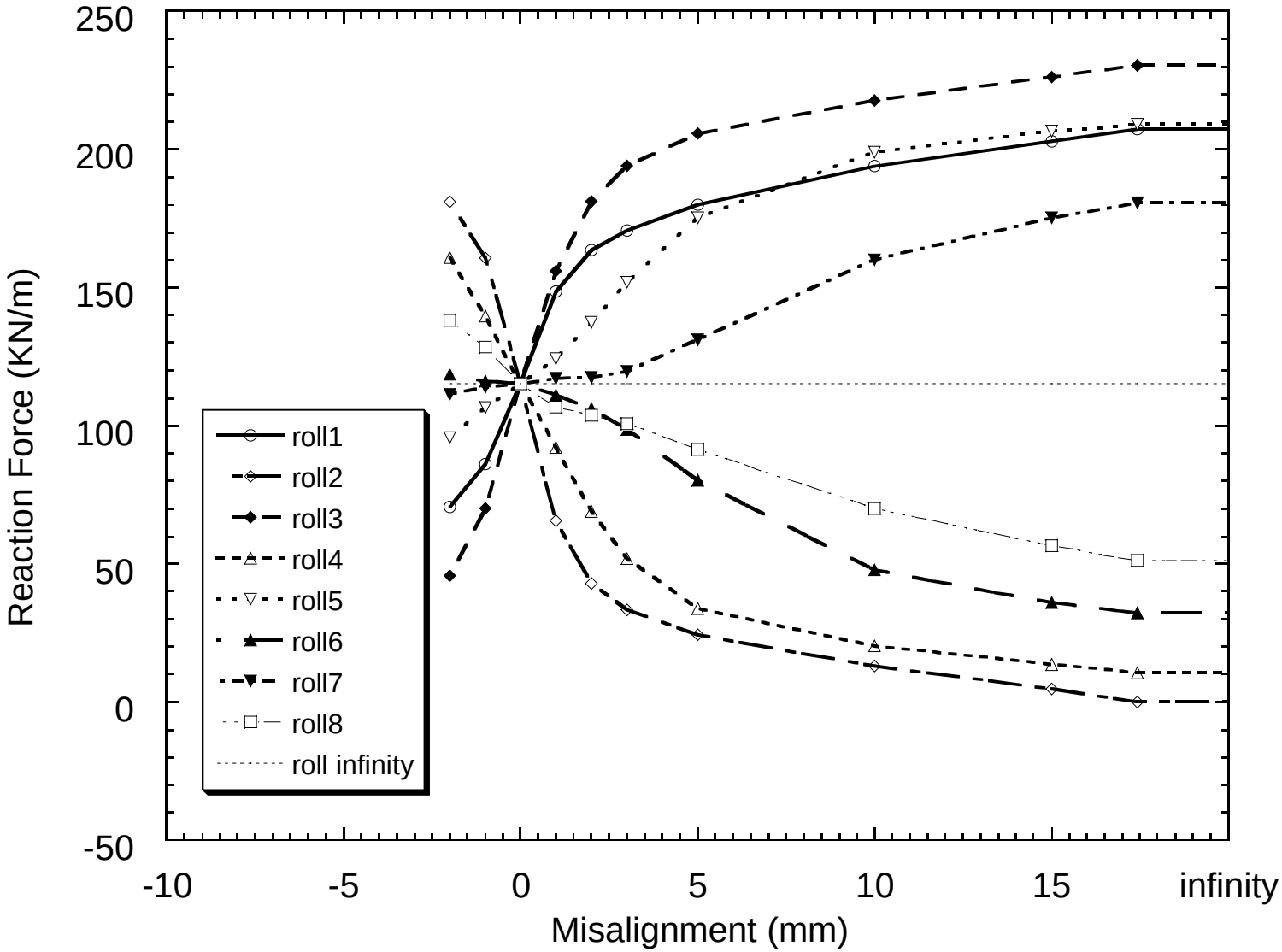
- Sudden roll pitch change leads to larger Max bulge and much larger Negative bulge, but the change in Max tensile strain on solidification front is not as significant as that of Max bulge and Neg bulge.
- Maximum bulge is at about 60% of the roll pitch from the upstream roll.
- Transient effect of sudden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

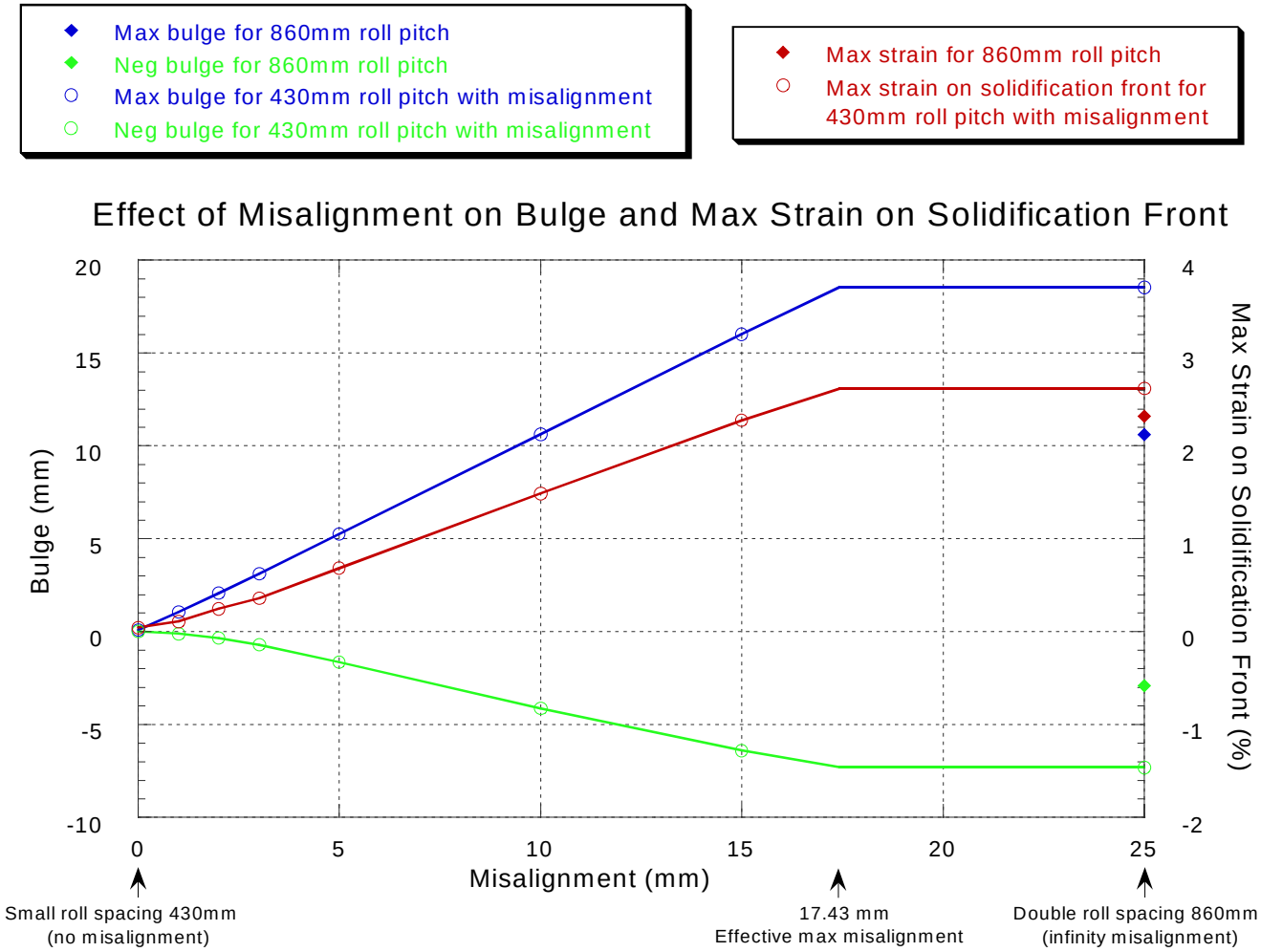
Effect of roll misalignment on bulging



Effective Maximum Misalignment = 17.43 mm

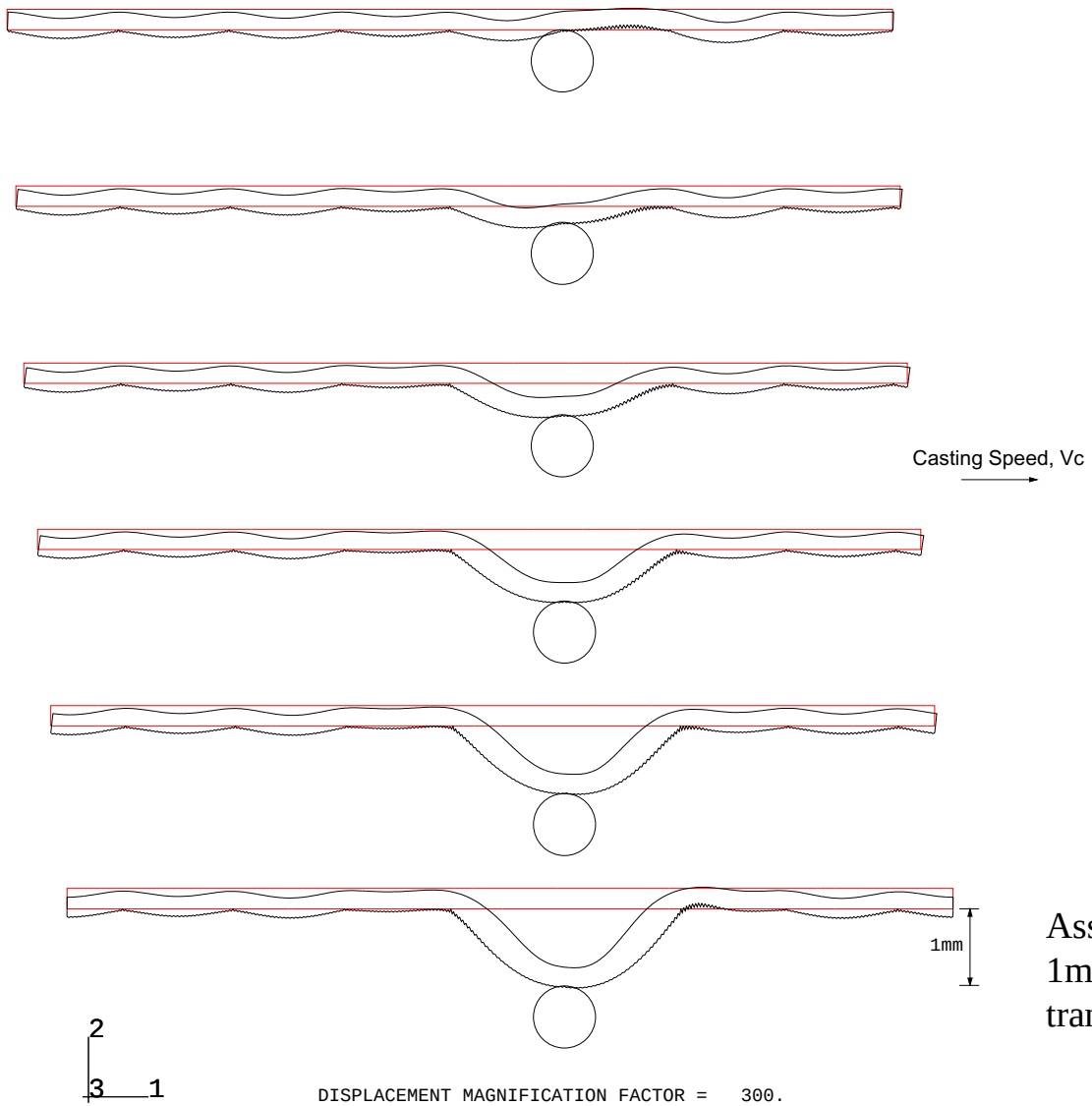
Effect of roll misalignment on reaction force





- 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.

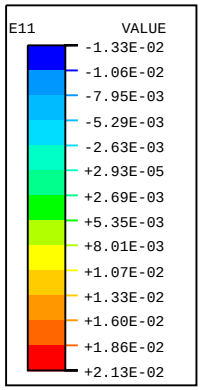
Warped roll simulation



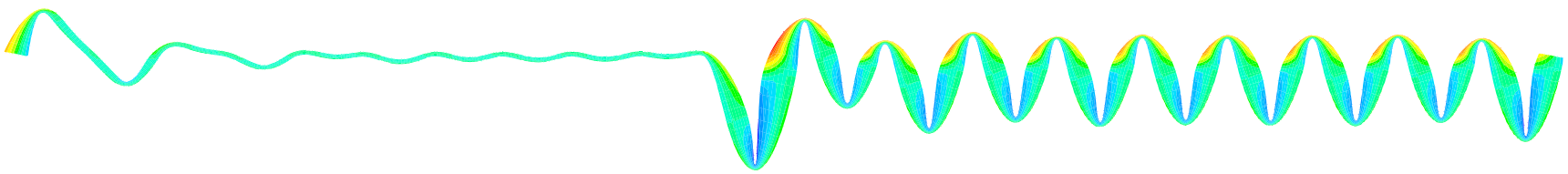
Assume misalignment caused by 1mm-warping of roll due to transient thermal distortion.

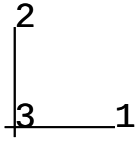
Strain contour plot for roll pitch changing from 250mm to 310mm

Total Strain
in X direction

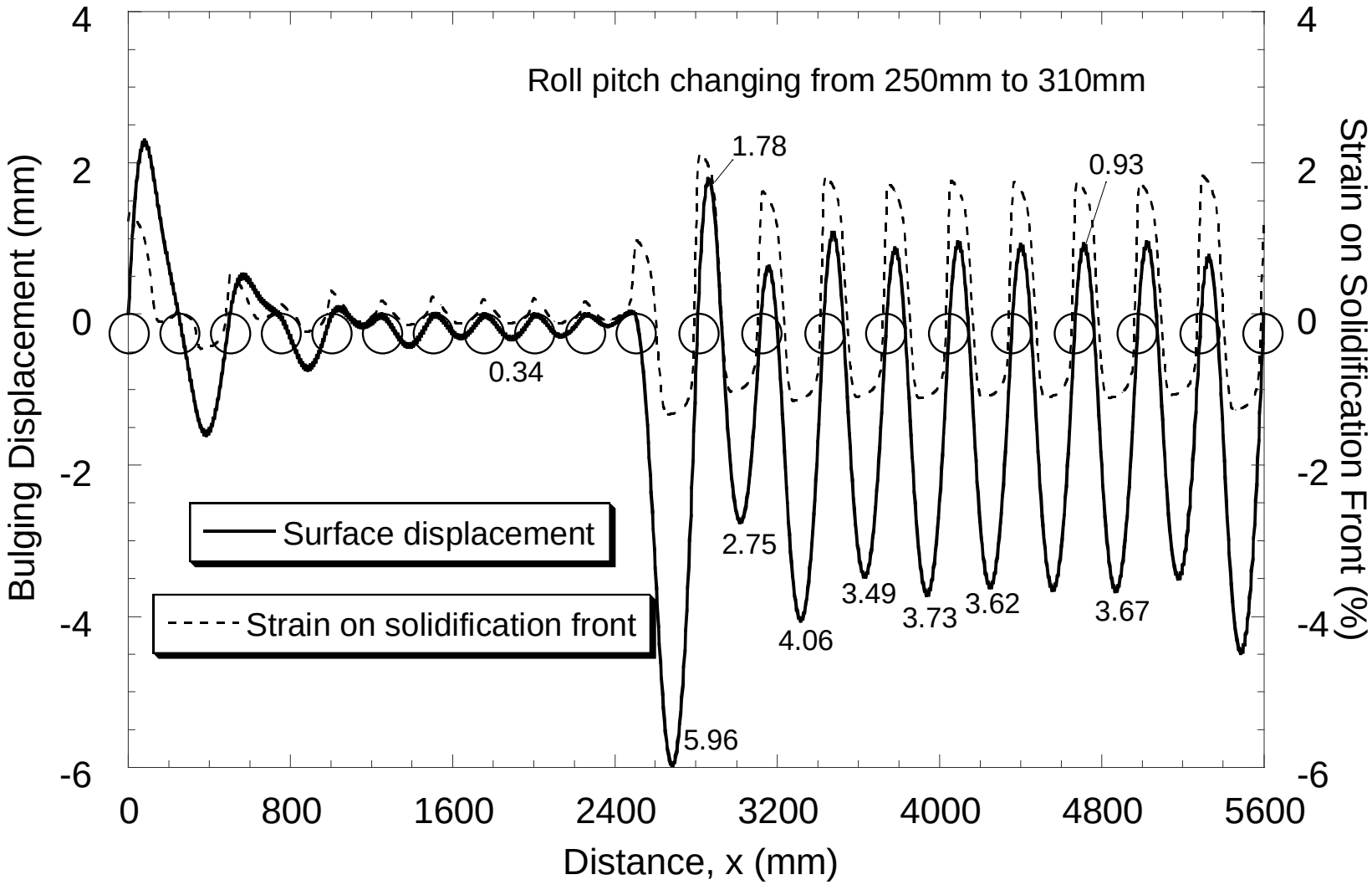


Roll pitch changing from 250mm to 310mm





DISPLACEMENT MAGNIFICATION FACTOR = 70.0
RESTART FILE = continue7 STEP 266 INCREMENT 8
TIME COMPLETED IN THIS STEP 1.01 TOTAL ACCUMULATED TIME 463.
ABAQUS VERSION: 5.8-1 DATE: 18-JAN-2000 TIME: 10:32:46


Roll pitch changing from 250mm to 310mm
Bulging Displacement (mm)
Strain on Solidification Front (%)
Distance, x (mm)
Surface displacement
Strain on solidification front
1.78
0.93
0.34
2.75
4.06
3.49
3.73
3.62
3.67
5.96
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.

Bulging Prediction Equation

- 2-D shape factor based on plate bending theory

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

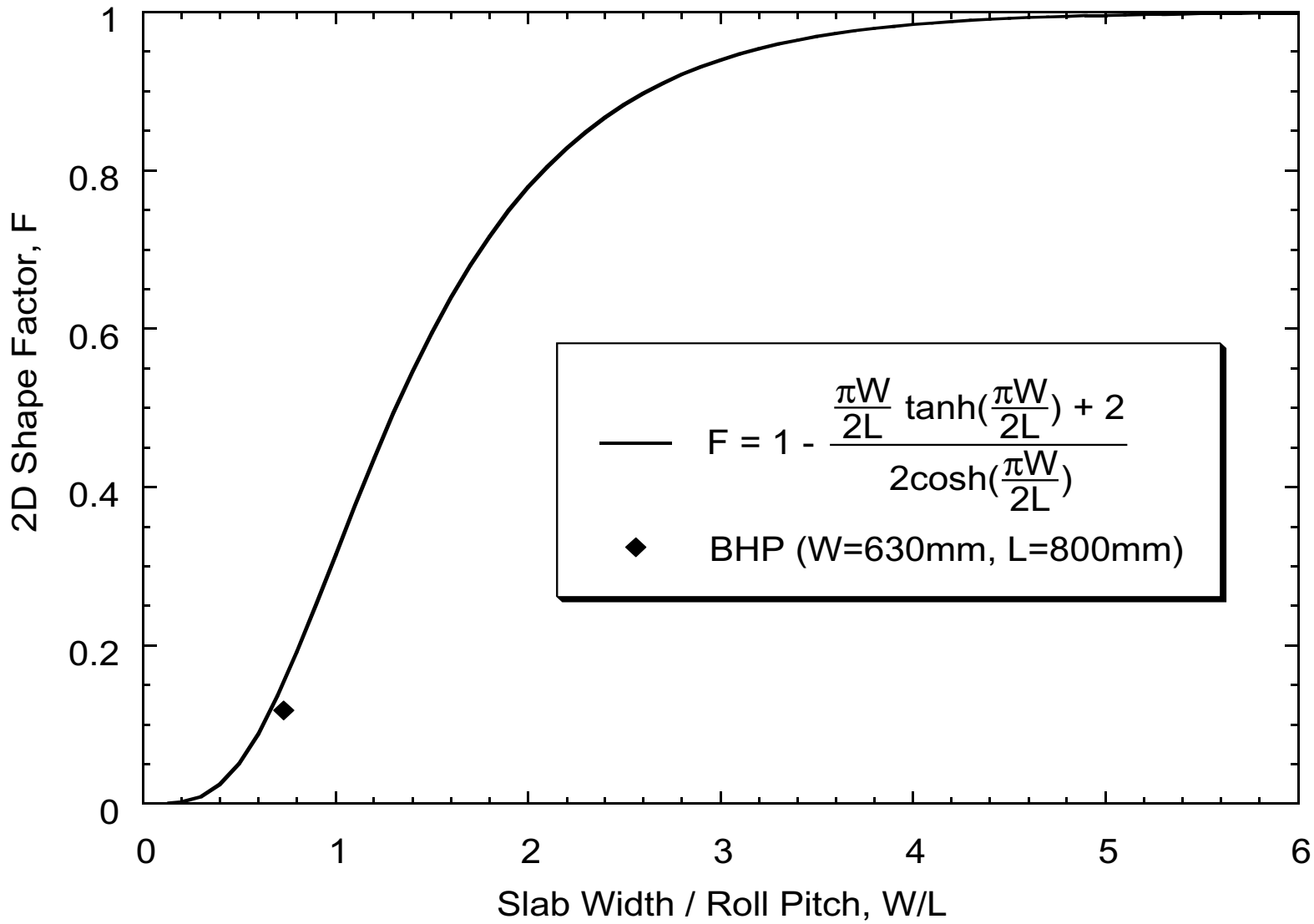
- Bulging prediction equation based on the parametric study for plain carbon steel

$$d_{\max}(mm) = 7.1496 \times 10^{-34} F \frac{L_{(mm)}^{6.5} P_{(MPa)}^{1.993} T_{surf\,(^\circ C)}^{8.766}}{D_{(mm)}^{5.333}}$$

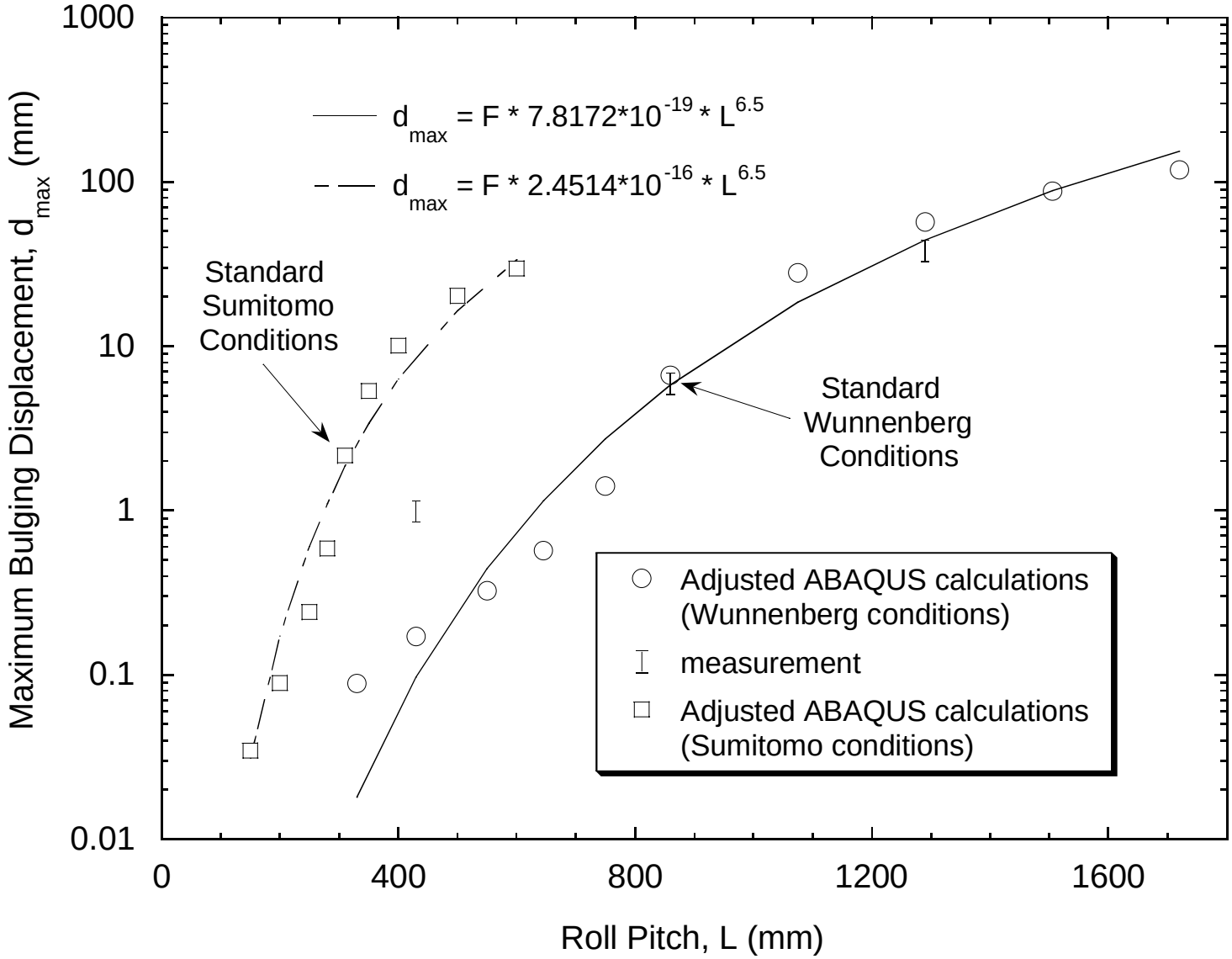
- Equation to predict strain at solidification front

$$\varepsilon_{\max}(mm) = 6.97 \times 10^{-31} F \frac{L_{(mm)}^{5.12} P_{(MPa)}^{2.08} T_{surf\,(^\circ C)}^{8.67}}{D_{(mm)}^{5.01}}$$

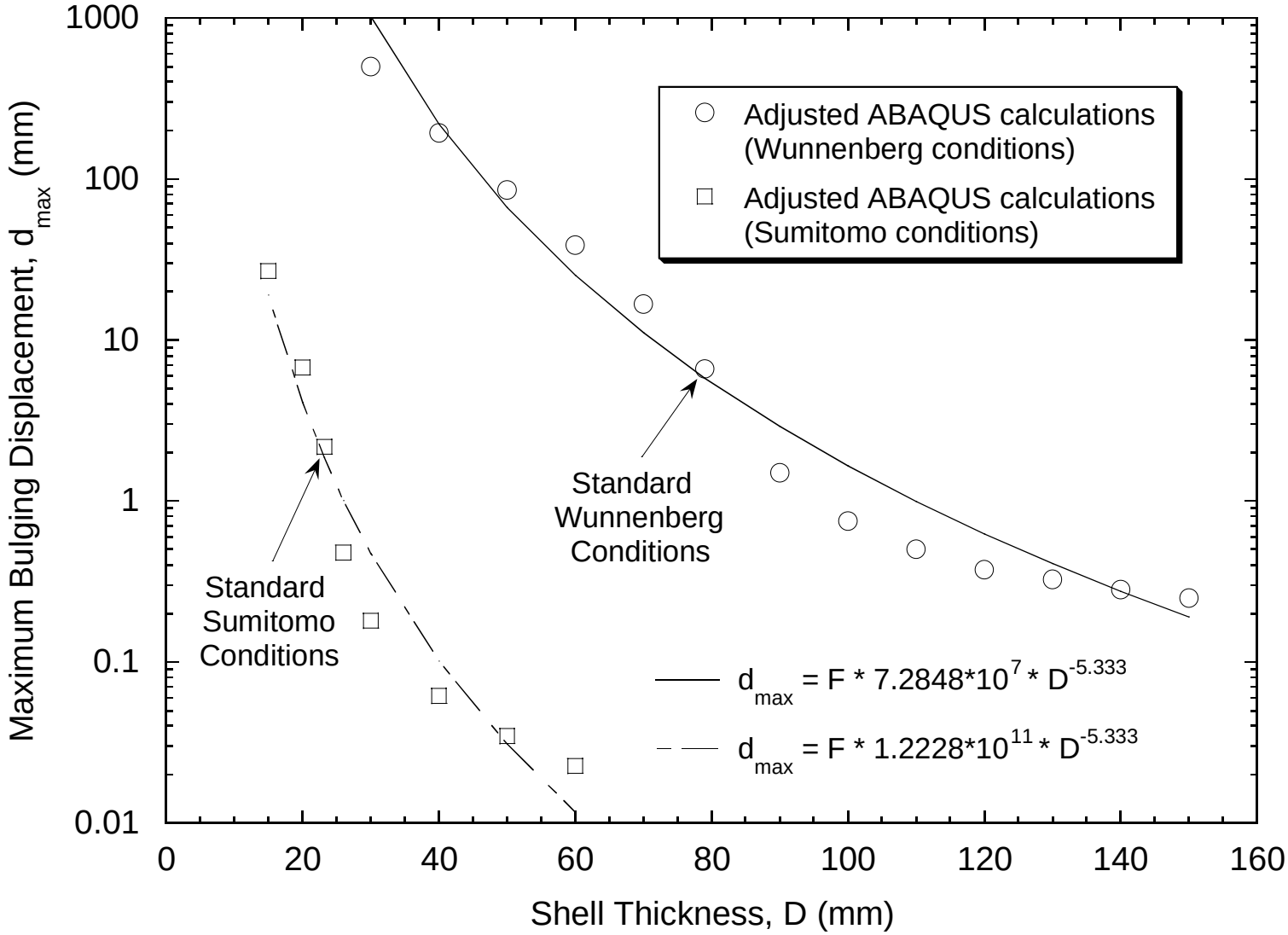
2D Shape Factor



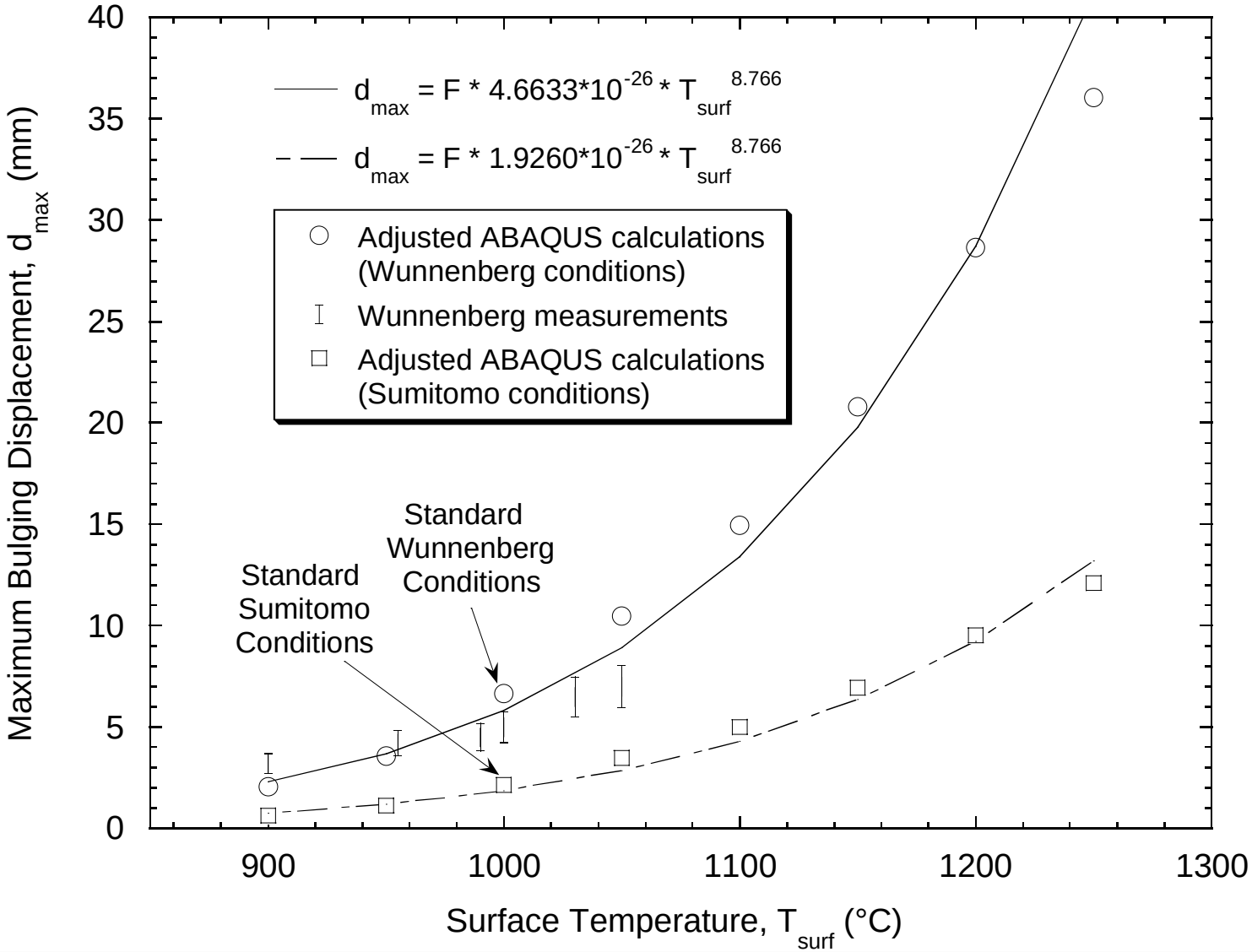
Roll Pitch Study



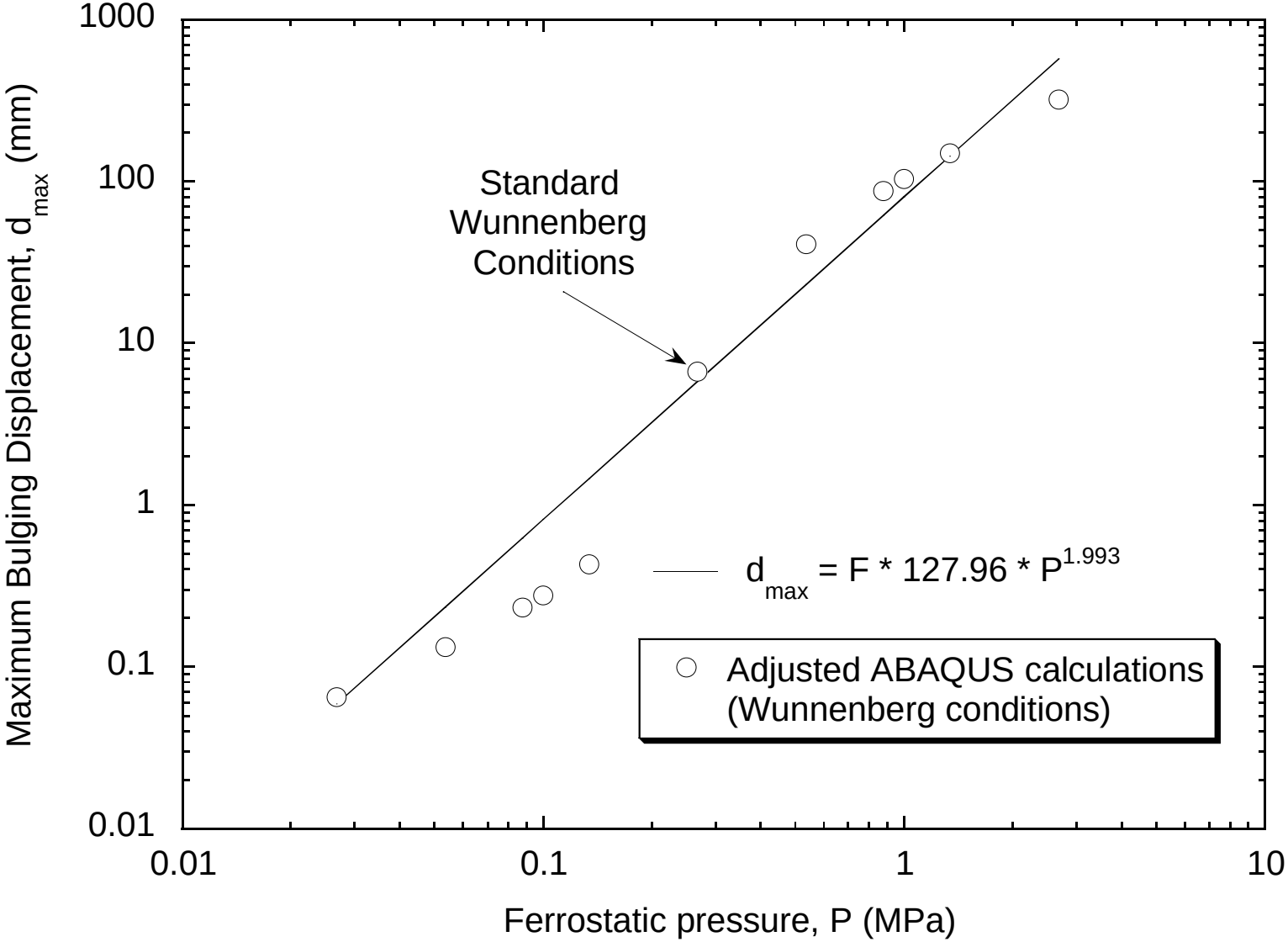
Shell Thickness Study



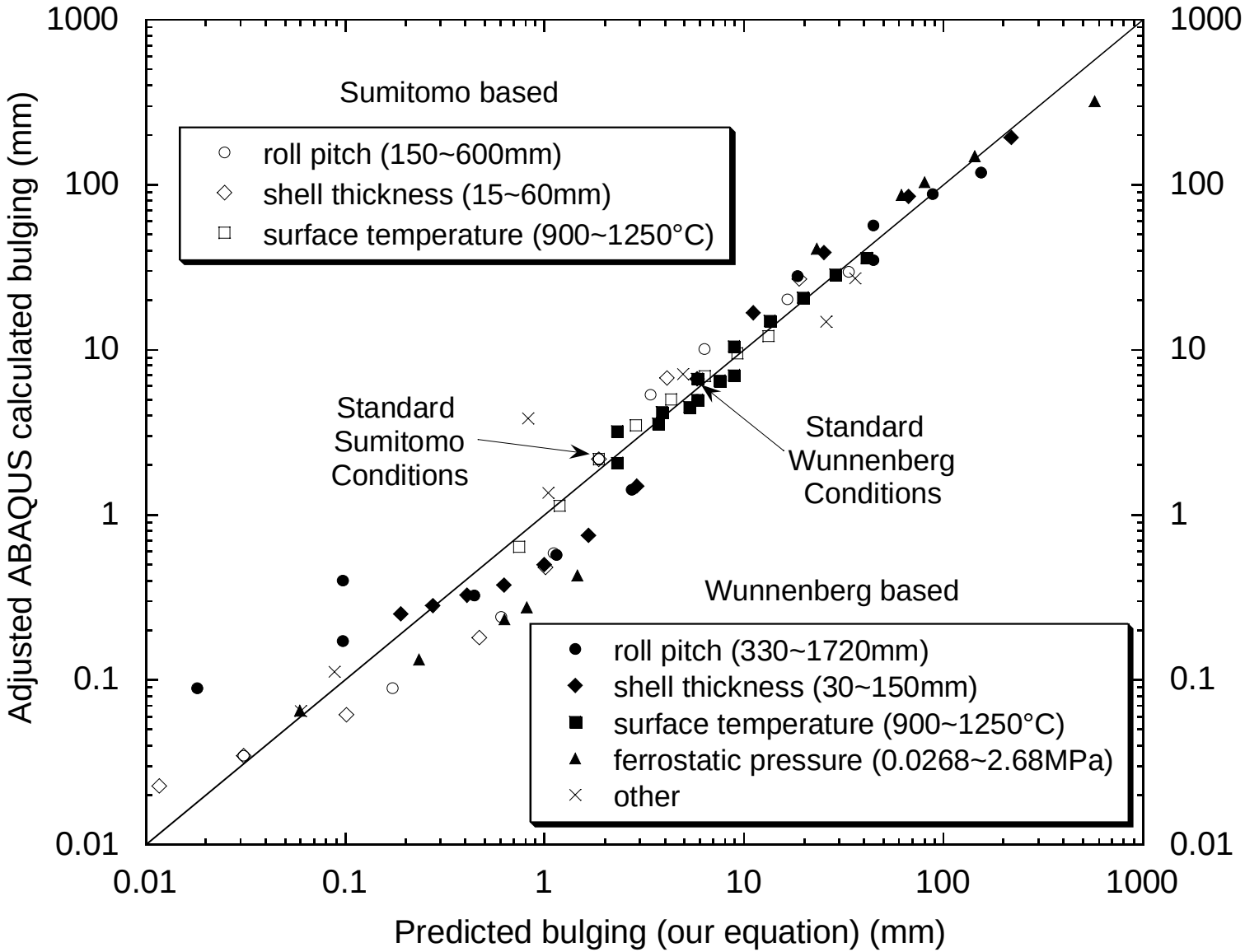
Surface Temperature Study



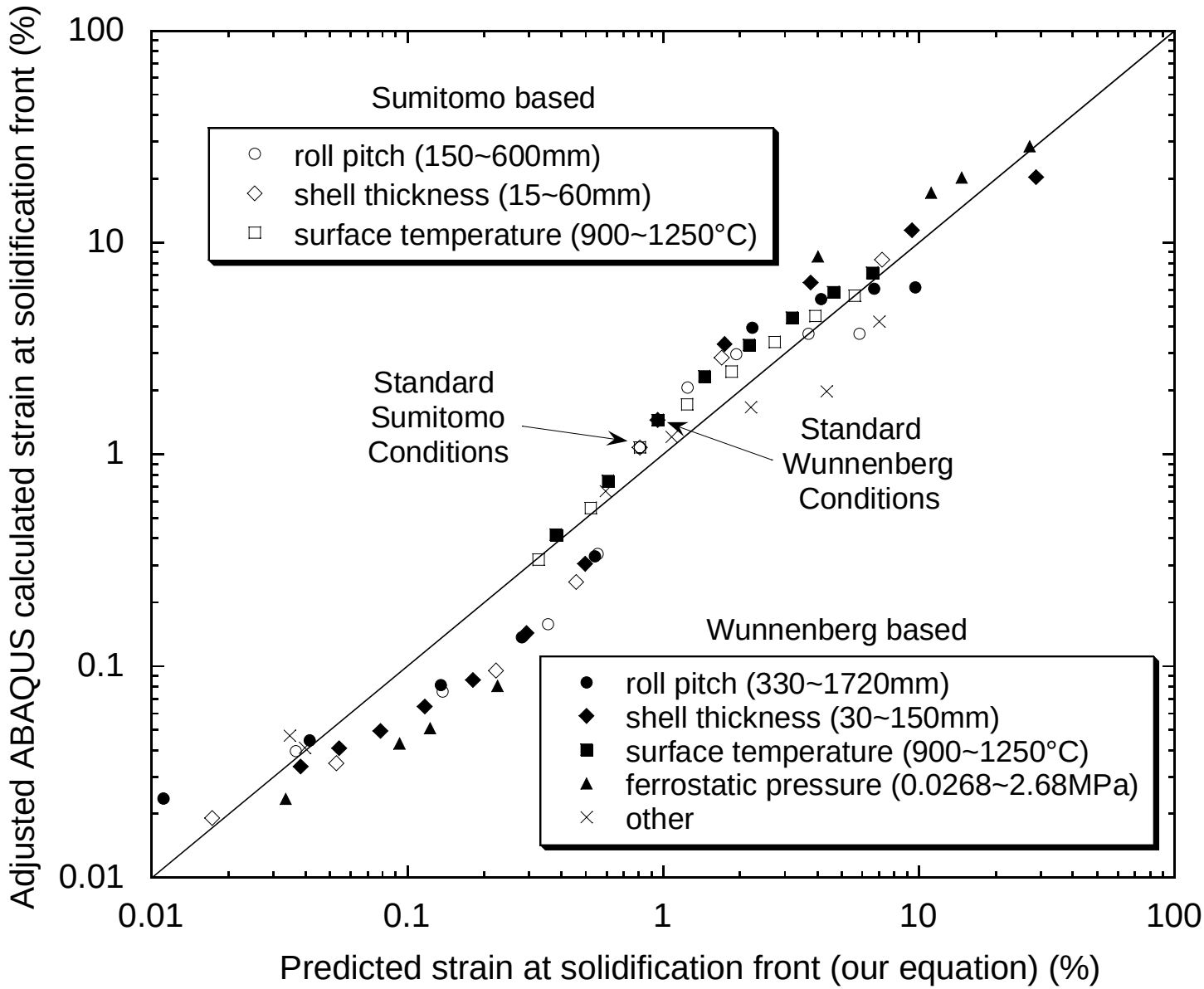
Ferrostatic Pressure Study



Comparison of bulging prediction equation with ABAQUS results



Comparison of strain prediction equation with ABAQUS results



Evaluation of Empirical Bulging Prediction Equations

- Okamura Equation (based on FEM simulations):

$$d_{\max}(mm), \varepsilon_b(\%) = AD_{(mm)}^{j} P_{(kg/mm^2)}^{k} L_{(mm)}^{l} T_{surf(°C)}^{m} V_{c(m/\min)}^{n}$$

where,

	A	j	k	l	m	n
$d_{\max}$	$10^{0.102D-20.3}$	-4.23	2.75	6.34	$-3.58\times10^{-2}D+4.94$	$-6.5\times10^{-4}D-0.065$
ε_b	$10^{0.163D-22.7}$	-4.23	2.9	5.01	$-5.52\times10^{-2}D+6.78$	$-6.5\times10^{-4}D-0.065$

- Palmaers Equation (based on beam bending analysis):

$$d_{\max}(mm) = 0.4623C(T_{surf})\frac{P_{(kg/mm^2)}^{1.5} L_{(mm)}^{5.12}}{V_{c(m/\min)}^{0.22} D_{(mm)}^{3.8}}$$ where, $$C(T_{surf}) = \begin{cases} 0.609\times10^{-4} & T_{surf} = 900°\text{C} \\ 0.725\times10^{-4} & T_{surf} = 1000°\text{C} \\ 0.929\times10^{-4} & T_{surf} = 1100°\text{C} \end{cases}$$

- Lamant Equation (based on beam bending analysis):

$$d_{\max}(mm) = 7.4088\times10^{-14}\exp(0.003866(T_{surf(°C)}+273))\frac{L_{(mm)}^{7.16} H_{(m)}^{2.18}}{V_{c(m/\min)}^{0.4} D_{(mm)}^{5.47}}$$

- Nippon Steel

$$d_{\max}(mm) = 1.893\times10^{-3}\exp\left(\frac{-5755}{T_{surf(°C)}+273}\right)\frac{L_{(mm)}^{3.3} P_{(kg/cm^2)}^{1.22}}{D_{(mm)}^{2.85}}$$

China Steel Casting Conditions

	Air Mist (0.39 l/kg steel)
Casting Speed: (m/min)	0.55
Pour Temperature: (^oC)	1551
Slab Geometry: (mm*mm)	1560*270
Nozzle Submergence Depth: (mm)	200
Working Mold Length: (mm)	600
Carbon Content: (%)	0.159
Mold Oscillation Frequency: (cpm)	120
Oscillation Stroke: (mm)	4
Mold Thickness (with Water Channel): (mm)	51
Initial Mold Cooling Water Temperature: (^oC)	35
Water Channel Geometry (depth*width*distance): (mm^3)	21*6*28
Cooling Water Flow rate: (m/s)	6.41

Model Validation:China Steel

Spray Zones Variables

Ambient temperature below spray zones: 35ºC
Spray zone coefficients: A=1.57, n=0.55, b=0.0075
Minium convection heat transfer coefficient (natural): 8.7(W/m^2K)

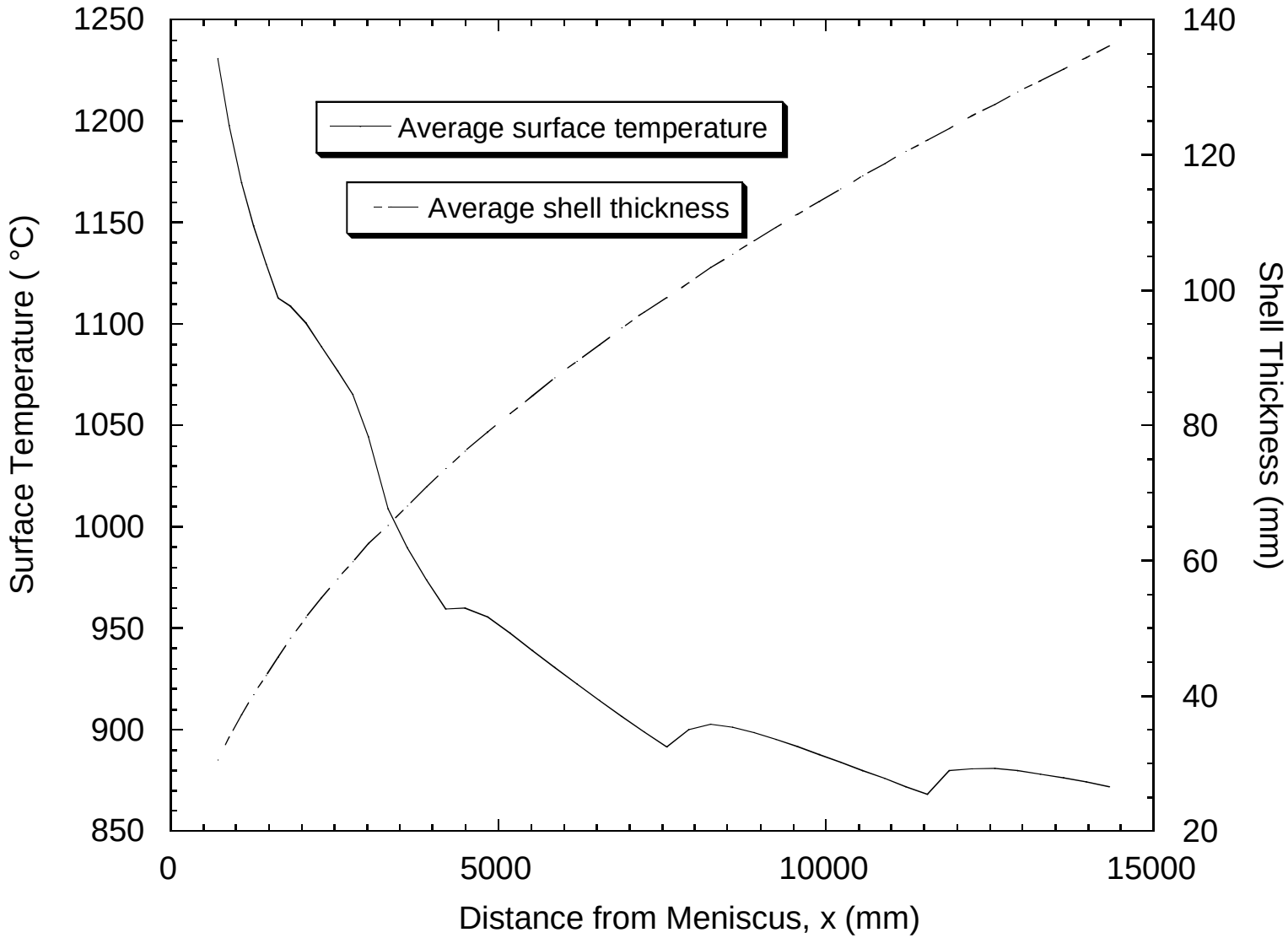
Air Mist

No.	zone starts (mm)	#	rol. rad. (m)	water flowrate (l/min/row)	spray width (m)	spray length (m)	contct angle (Deg)	frac.of q thr rol	spray coeff	conv. coeff. (W/m^2K)	amb. temp. (DegC)
1	600.0	2	.0700	19.250	1.600	.040	7.00	.050	0.25	8.7	35
2	891.2	5	.0700	9.900	1.600	.060	7.00	.050	0.25	123.0	35
3	1824.2	5	.1000	8.800	1.600	.060	7.00	.050	0.25	109.0	35
4	3018.4	5	.1250	9.900	1.400	.060	7.00	.200	0.25	123.0	35
5	4491.8	10	.1500	8.250	1.400	.060	7.00	.200	0.25	102.0	35
6	7908.6	12	.1400	5.275	1.400	.060	7.00	.220	0.25	65.0	35
7	11878.4	15	.1550	2.570	1.200	.060	7.00	.300	0.25	32.0	35
8	17111.0	9	.2400	0.000	9.999	.060	7.00	.250	0.25	8.7	400
	21678.1		End of last spray zone (mm)								

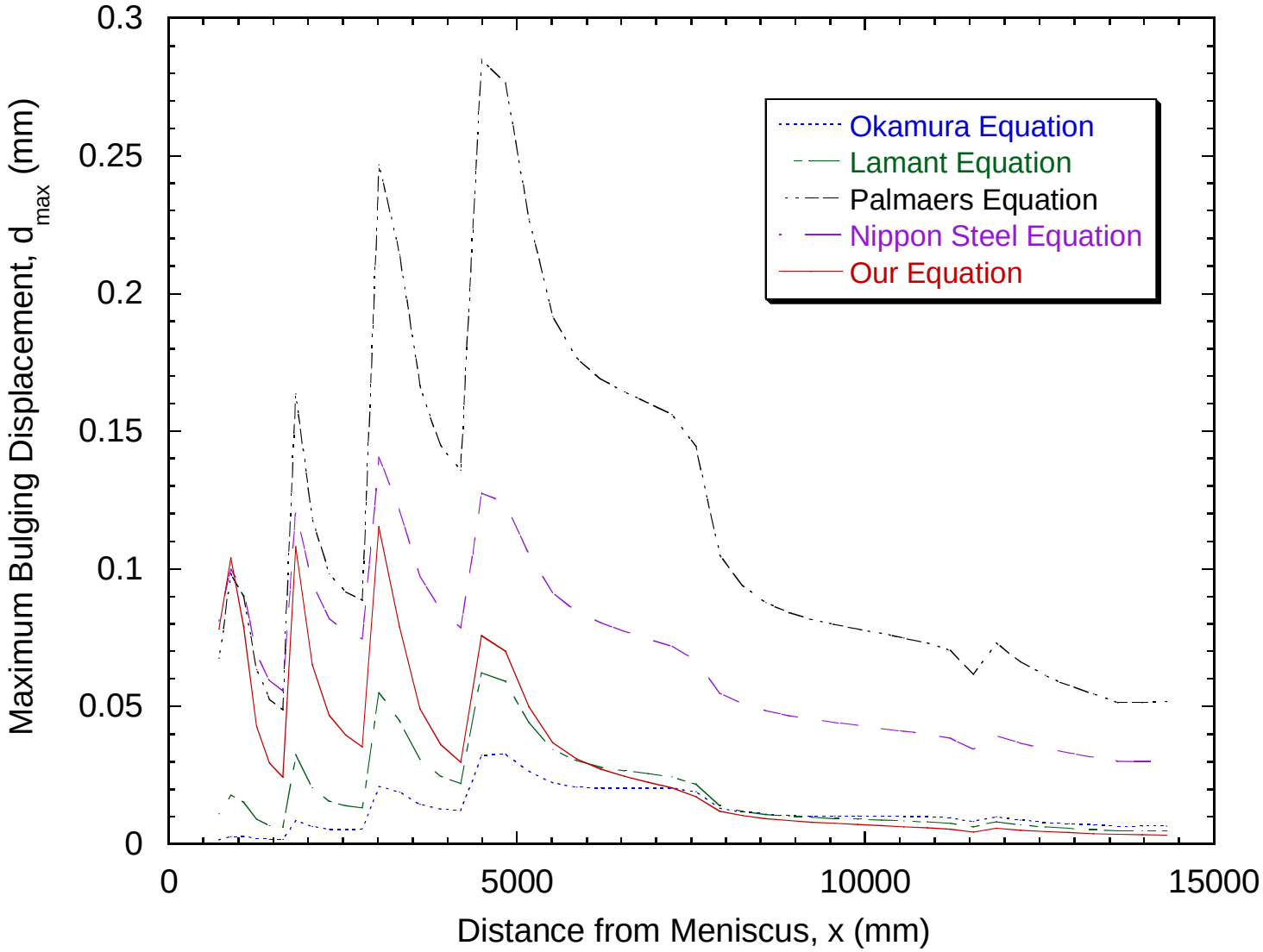
China steel, Vc=0.55 m/min: CON1D results

Roll/Pitch No.	upper roller,mm	lower roller,mm	roller pitch,mm	average pressure between the roll, Pa	avg shell thickness, mm	surface temperature, °C
1	720.1	891.2	171.1	55265.7	21.1	1230.8
2	891.2	1077.8	186.6	67514.2	22.9	1197.8
3	1077.8	1264.4	186.6	80277.2	24.7	1169.6
4	1264.4	1451.0	186.6	93019.5	28.4	1148.2
5	1451.0	1637.6	186.6	105737.0	31.1	1129.5
6	1637.6	1824.2	186.6	118425.6	32.9	1112.7
7	1824.2	2063.1	238.8	132846.4	34.8	1108.8
8	2063.1	2301.9	238.8	148981.9	39.5	1100.5
9	2301.9	2540.7	238.8	165046.8	42.9	1088.8
10	2540.7	2779.6	238.8	181032.4	45.0	1076.9
11	2779.6	3018.4	238.8	196930.3	46.6	1065.2
12	3018.4	3313.1	294.7	214565.5	48.2	1044.3
13	3313.1	3607.8	294.7	233899.4	50.5	1008.9
14	3607.8	3902.4	294.7	253056.7	55.0	989.7
15	3902.4	4197.1	294.7	272021.6	58.3	973.9
16	4197.1	4491.8	294.7	290778.8	60.5	959.5
17	4491.8	4833.5	341.7	310770.9	62.4	960.0
18	4833.5	5175.1	341.7	331939.0	64.5	955.7
19	5175.1	5516.8	341.7	352762.1	69.3	947.6
20	5516.8	5858.5	341.7	373217.3	73.8	939.0
21	5858.5	6200.2	341.7	393282.2	76.7	930.6
22	6200.2	6541.9	341.7	412934.8	78.8	922.4
23	6541.9	6883.6	341.7	432153.7	80.5	914.4
24	6883.6	7225.2	341.7	450917.6	82.1	906.5
25	7225.2	7566.9	341.7	469206.1	83.6	898.9
26	7566.9	7908.6	341.7	486999.2	86.3	891.5
27	7908.6	8239.4	330.8	504010.7	91.5	900.2
28	8239.4	8570.2	330.8	520239.2	95.5	902.7
29	8570.2	8901.1	330.8	535950.7	98.3	901.2
30	8901.1	9231.9	330.8	551129.2	100.4	898.5
31	9231.9	9562.7	330.8	565759.0	102.1	895.3
32	9562.7	9893.5	330.8	579825.2	103.5	891.7
33	9893.5	10224.3	330.8	593313.2	104.8	887.8
34	10224.3	10555.1	330.8	606209.2	106.0	883.9
35	10555.1	10886.0	330.8	618499.9	107.3	879.9
36	10886.0	11216.8	330.8	630172.8	108.5	876.0
37	11216.8	11547.6	330.8	641215.8	110.2	872.0
38	11547.6	11878.4	330.8	651617.6	114.6	868.2
39	11878.4	12227.3	348.8	661614.6	119.1	879.8
40	12227.3	12576.1	348.8	671159.2	123.0	880.7
41	12576.1	12924.9	348.8	679956.6	126.1	880.9
42	12924.9	13273.8	348.8	687996.8	128.7	879.9
43	13273.8	13622.6	348.8	695270.5	131.1	878.1
44	13622.6	13971.5	348.8	701769.5	133.5	876.3
45	13971.5	14320.3	348.8	707486.3	133.8	874.3
46	14320.3	14669.1	348.8	712432.7	133.8	871.9

China Steel – CON1D results



Comparison of Different Models (China Steel)



Comparison of Different Models

Bulging (mm) with 2D shape factor		Okamura Equation	Lamant Equation	Palmaers Equation	Nippon Steel Equation	Our Equation	Bulging Measurement
Wunnenberg based (roll pitch)	430mm	0.028	0.060	0.279	0.127	0.097	0.4~1.6
	860mm	1.505	5.666	6.406	0.830	5.809	5~7
	1290mm	10.787	56.612	27.991	1.734	44.414	35~42
Wunnenberg based (surface temperature)	900°C	1.205	3.849	5.381	0.564	2.306	3.2
	955°C	1.366	4.761	5.945	0.703	3.879	4.2
	990°C	1.473	5.451	6.304	0.801	5.319	4.5
	1000°C	1.505	5.666	6.406	0.830	5.809	5
	1030°C	1.602	6.362	6.947	0.921	7.527	6.5
	1050°C	1.668	6.874	7.307	0.985	8.909	7
Sumitomo based (roll pitch)	310mm	0.465	1.831	1.730*	0.880	1.867**	3.2
	250mm	0.156	0.514	0.754*	0.567	0.605**	<1

* 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.

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