CCC Report
October 18, 2001

Thermal Stress Analysis of Bulging with Roll Misalignment for Various Slab Cooling Patterns

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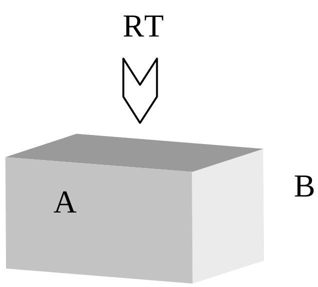
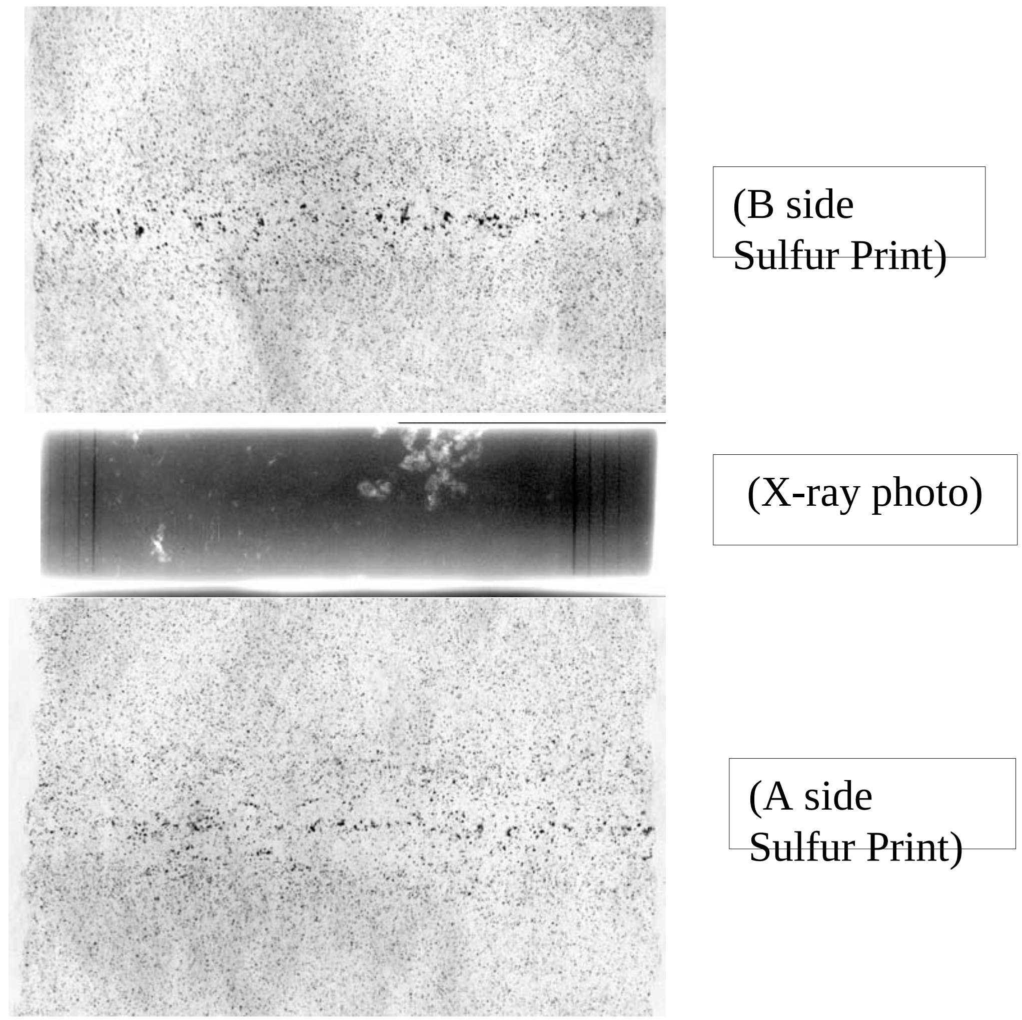
Quality Concerns for Heavy Plate

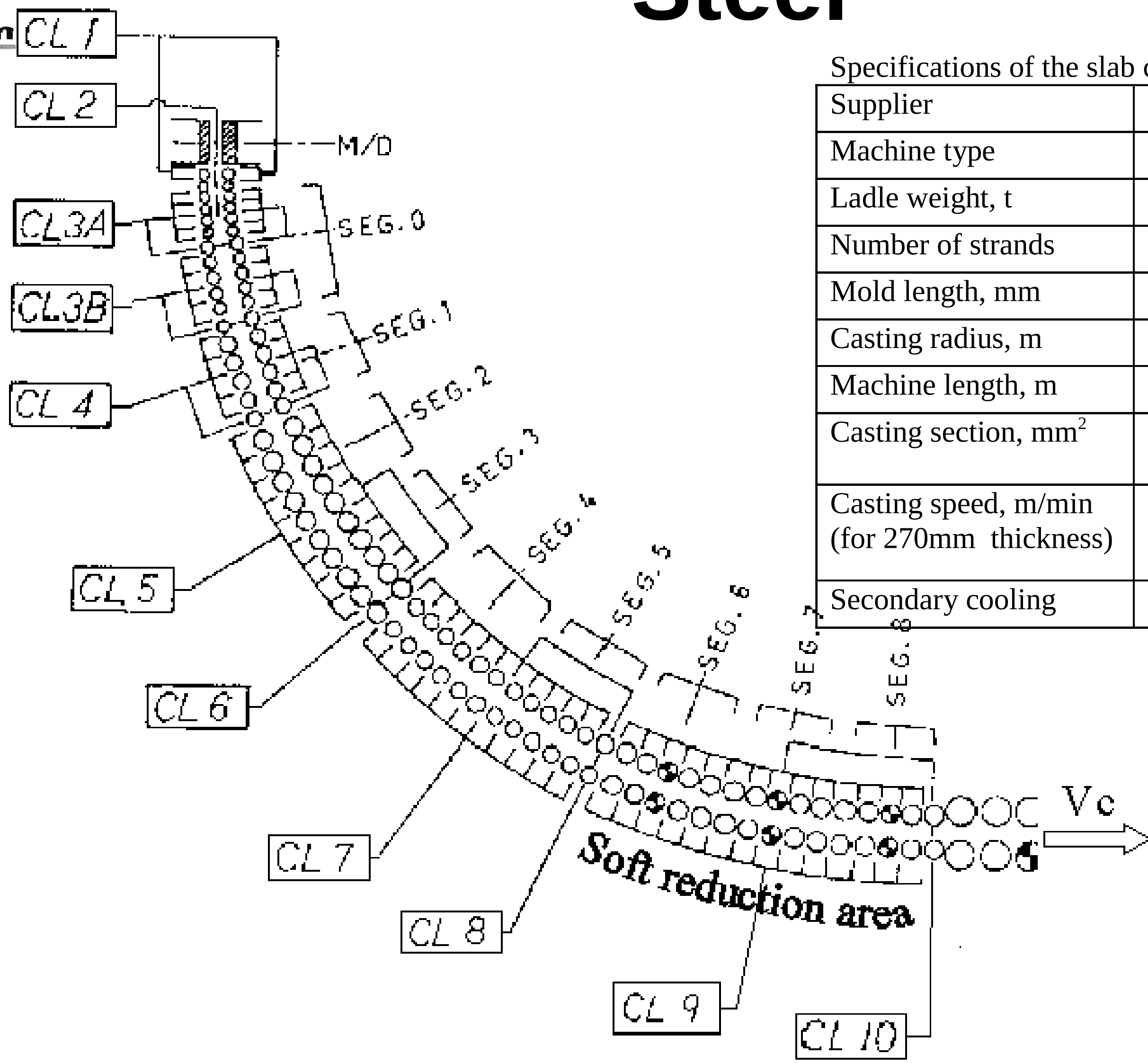
- Main defects in plate inspection
  - Low T/2 toughness
  - UT defects
    (correlated with centerline POROSITY)
- Low toughness is aggravated by
  - Bulging
  - Segregation
- Strong cooling may lessen shell bulging

Slab center porosity: cause of UT defects in heavy plate





Machine layout of #1SCC, China Steel

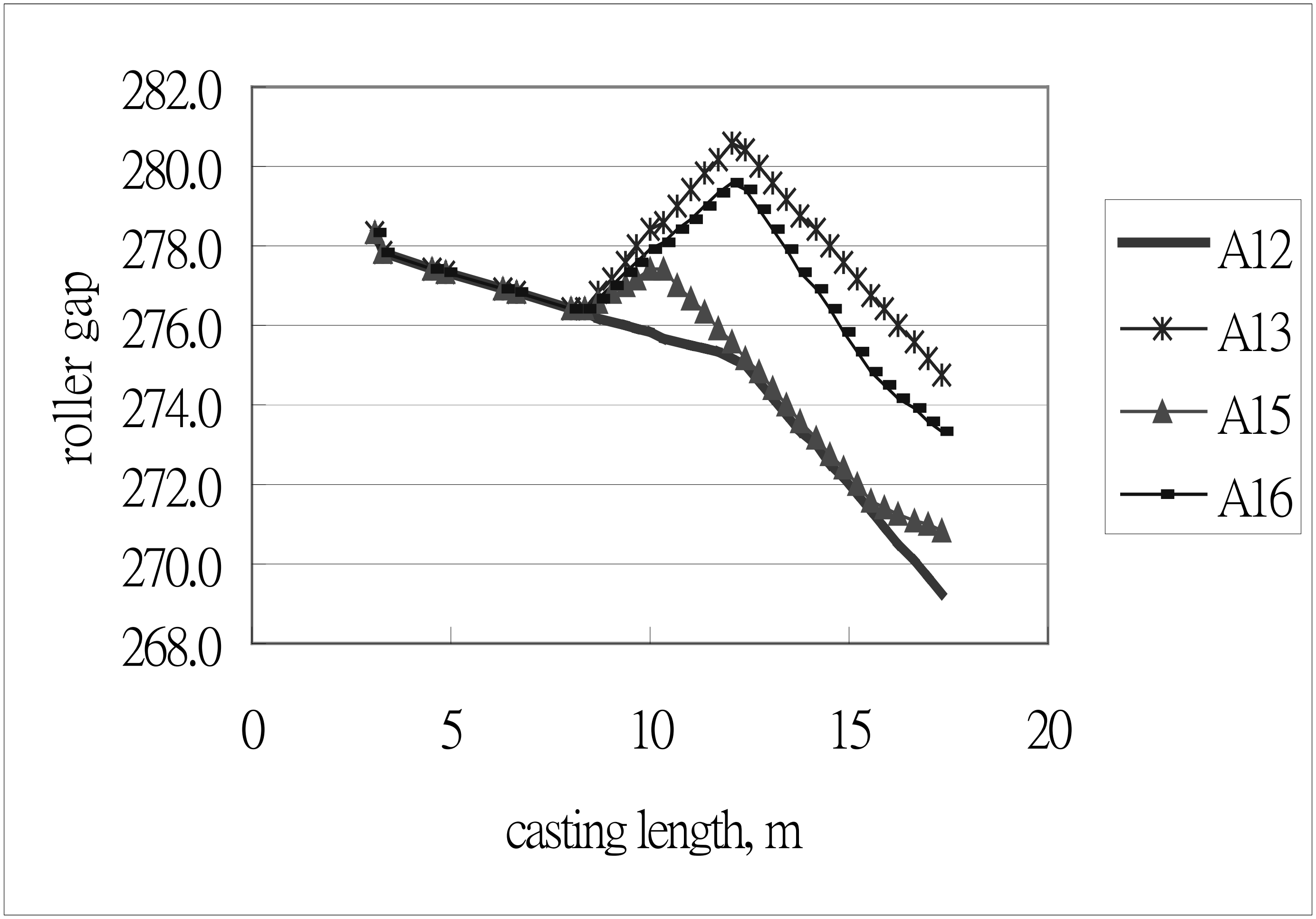


Specifications of the slab caster

Supplier	MDH
Machine type	Curve
Ladle weight, t	150
Number of strands	1x2
Mold length, mm	704
Casting radius, m	10.455
Machine length, m	22
Casting section, mm^2	180~270 x 950~1800
Casting speed, m/min (for 270mm thickness)	0.5~0.8
Secondary cooling	Air/Water mist

Roll gaps (machine taper) profile

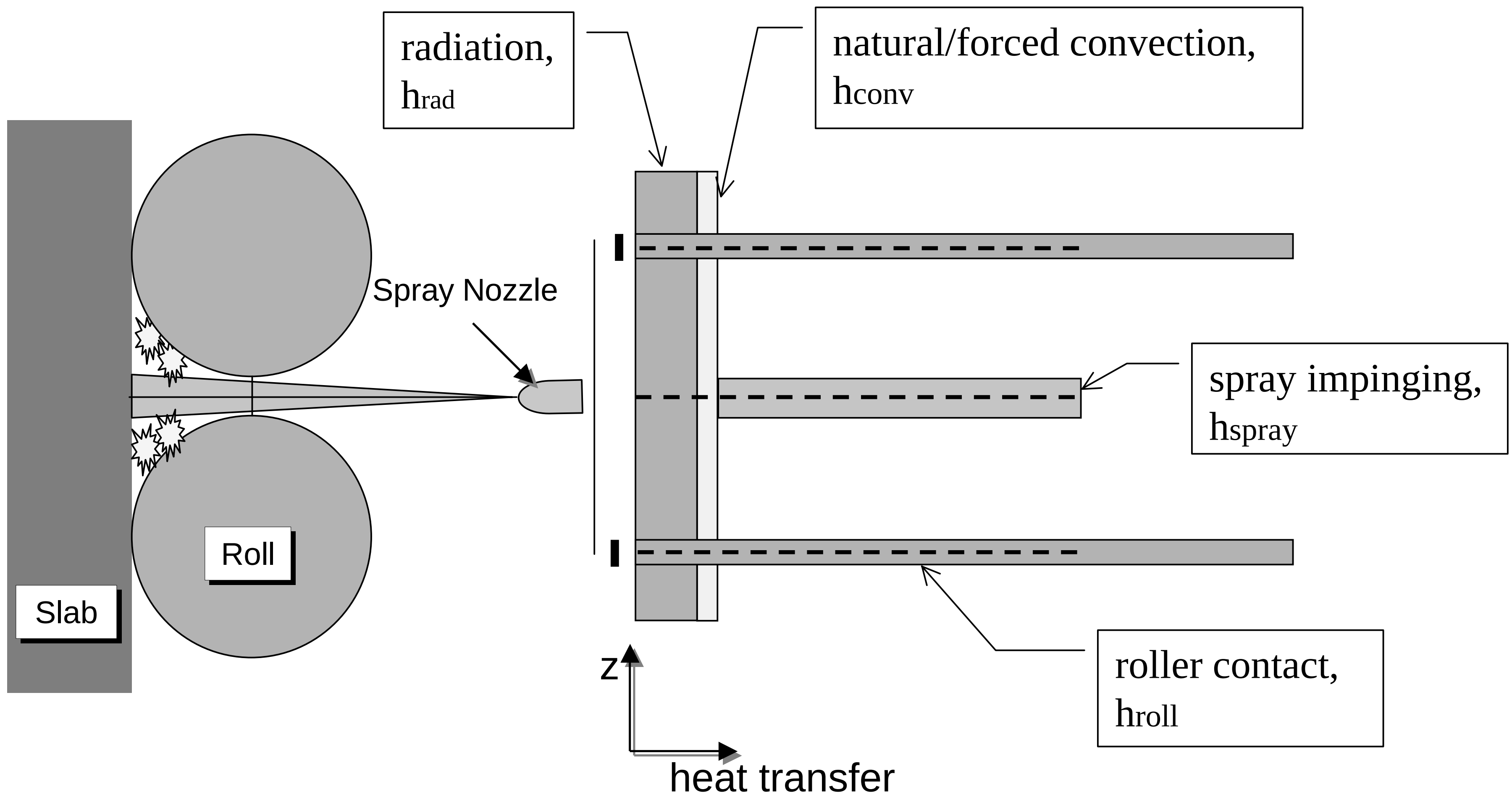
(used at China Steel for slab soft reduction)



Model Validation: China Steel

- In-slab thermocouple measurement
- Surface temperature measurement with optical pyrometers
- Heat extraction from support rolls from measuring machine water temperature increase

CON1D treatment of Spray Zone



Spray zone model

$$h_{rad} = \sigma \cdot \varepsilon_{steeel} \cdot (T_s + T_{amb}) \cdot (T_s^2 + T_{amb}^2)$$

$$h_{conv} = Max(8.7, 12.4 \cdot Q_W)$$

$$h_{spray} = Coeff \cdot A \cdot Q_w^n \cdot (1 - b \cdot T_{amb})$$

$$h_{roll} = \frac{(h_{rad} + h_{conv} + h_{spray}) \cdot L_{spray} + (h_{rad} + h_{conv}) \cdot (Pitch - L_{spray} - L_{roll\ contact})}{L_{roll\ contact} \cdot (1 - q)} \cdot q$$

Where, σ = Stefan Boltzman constant (5.67e-8W/m^{2}K^4)

ε_{steel} = steel emissivity (-)

T_s, T_{amb} = steel surface temperature, ambient temperature (K)

Q_w = water flux (l/m^{2}sec)

Coeff, A, n, b = coefficients for spray heat transfer (-)

L_{spray}, $L_{roll\ contact}$ = spray length, roll contact length (m)

q = fraction of heat flow per zone going to roll (-)

In-Slab Thermocouple Validation: (China Steel Conditions)

	Water Spray only	Air Mist
Casting Speed: (m/min)	0.55	0.56
Pour Temperature: (^{o}C)	1510	1522
Slab Geometry: (mm*mm)	1560*270	1880*270
Nozzle Submergence Depth: (mm)	200	200
Working Mold Length: (mm)	600	600
Carbon Content: (%)	0.45	0.45
Mold Oscillation Frequency: (cpm)	120	120
Oscillation Stroke: (mm)	4	4
Mold Thickness (with Water Channel): (mm)	51	51
Initial Mold Cooling Water Temperature: (^{o}C)	35	35
Water Channel Geometry (depth*width*distance): (mm^3)	25*5*28	21*6*28
Cooling Water Flow rate: (m/s)	7.62	6.41

Model Validation:China Steel Spray Zones Variables

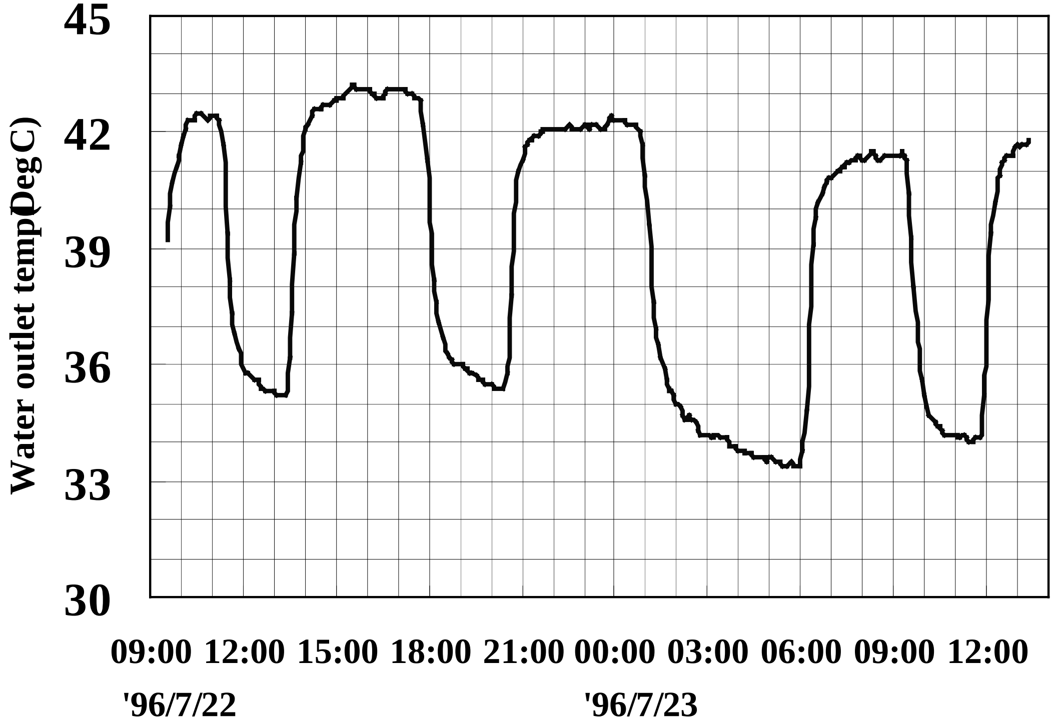
Ambient temperature below spray zones: 35°C
Spray zone coefficients: A=1.57, n=0.55, b=0.0075
Minium convection heat transfer coefficient (natural): 8.7(W/m^2K)

No.	zone starts (mm)	rol. #	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)
Water Spray only											
1	600.0	2	.0700	27.500	1.300	.050	7.00	.050	0.25	8.7	35
2	906.9	5	.0700	14.860	1.200	.050	7.00	.050	0.25	8.7	35
3	1840.8	5	.1000	14.860	1.200	.050	7.00	.050	0.25	8.7	35
4	3034.3	5	.1250	11.840	1.200	.050	7.00	.200	0.25	8.7	35
5	4520.5	10	.1500	8.800	1.200	.050	7.00	.200	0.25	8.7	35
6	7977.9	10	.1750	7.150	1.200	.050	7.00	.200	0.25	8.7	35
7	11883.1	11	.2100	2.500	2.000	.050	7.00	.200	0.25	8.7	35
8	17050.7	18	.2400	0.000	9.999	.050	7.00	.200	0.25	8.7	400
	26440.7	End of last spray zone (mm)									
Air Mist											
1	600.0	2	.0700	20.000	1.600	.040	7.00	.050	0.25	8.7	35
2	891.2	5	.0700	11.100	1.600	.060	7.00	.050	0.25	138.0	35
3	1824.2	5	.1000	9.800	1.600	.060	7.00	.050	0.25	121.0	35
4	3018.4	5	.1250	12.100	1.400	.060	7.00	.200	0.25	150.0	35
5	4491.8	10	.1500	8.300	1.400	.060	7.00	.200	0.25	103.0	35
6	7908.6	12	.1400	5.333	1.400	.060	7.00	.200	0.25	66.0	35
7	11878.4	15	.1550	0.000	1.200	.060	7.00	.330	0.25	8.7	400
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)									

Study of Roll-Contact Heat Extraction

S1 machine water outlet temperature

(13400 l/min for 2 strands; size: 210*1400mm)



Total removed heat = Flow rate*Density*Cp*ΔT

Heat extraction/roll ~ 21.1 KW/m

In-slab Temperature Measurement

- To validate models, temperature measurements were performed by embedding thermocouples in the solidifying slab.
- Conduct experiments a few meters before sequence end, to lessen process impact and strengthen wires.

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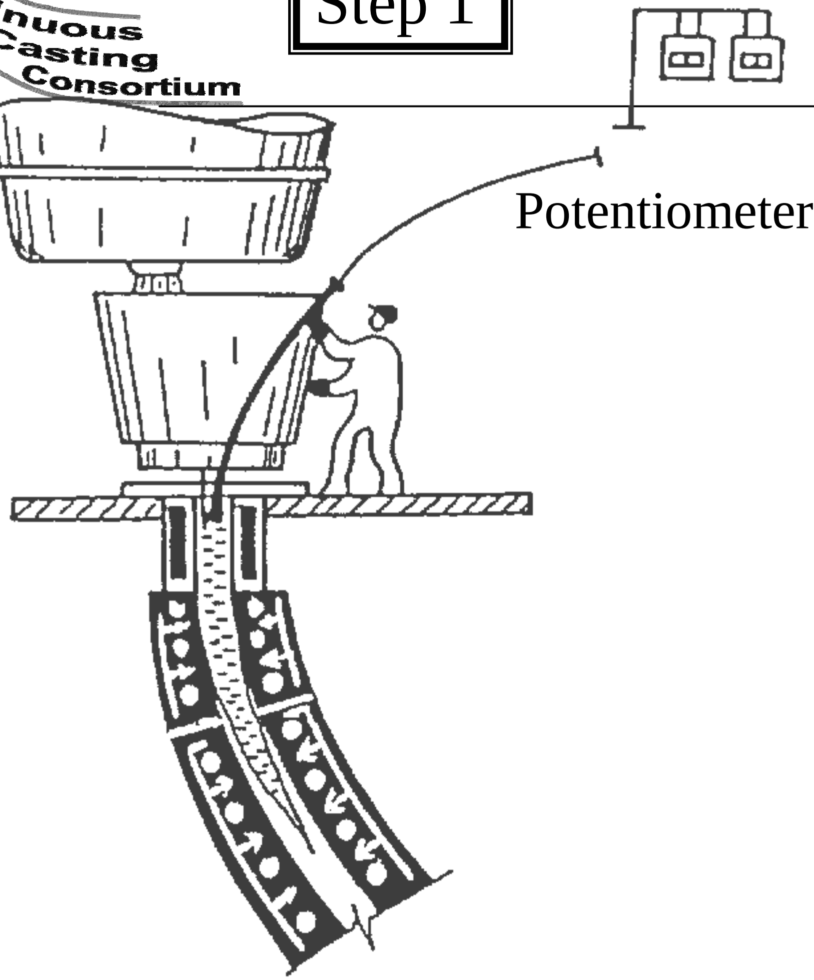
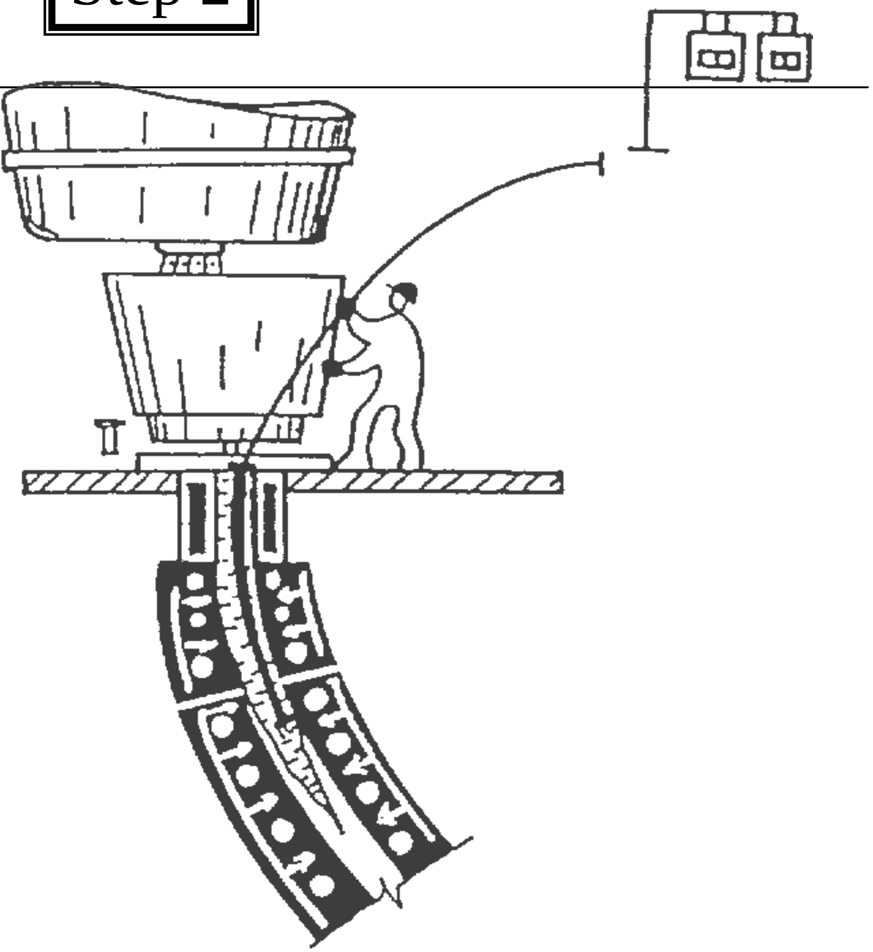
Step 1



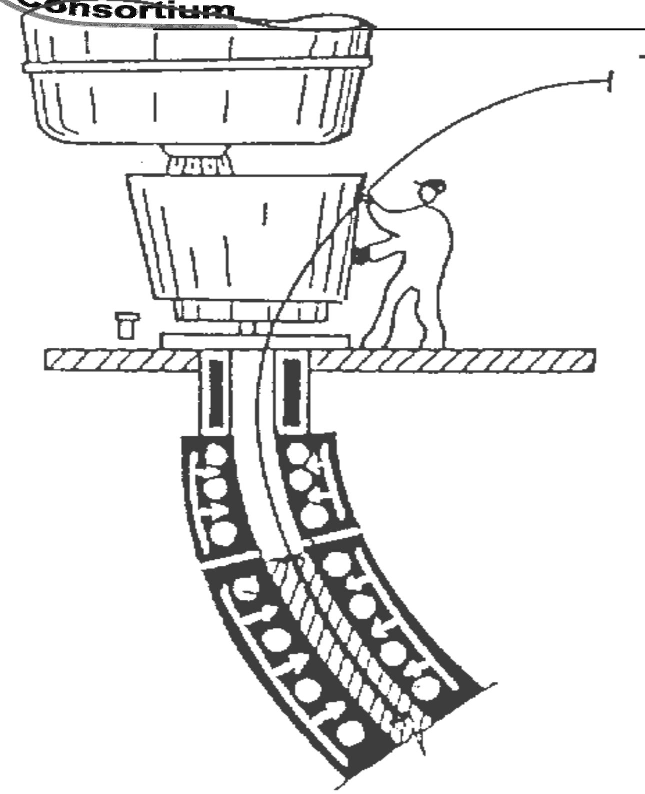
- Insert thermocouple block into mold top and freeze it into solid shell

Step 2

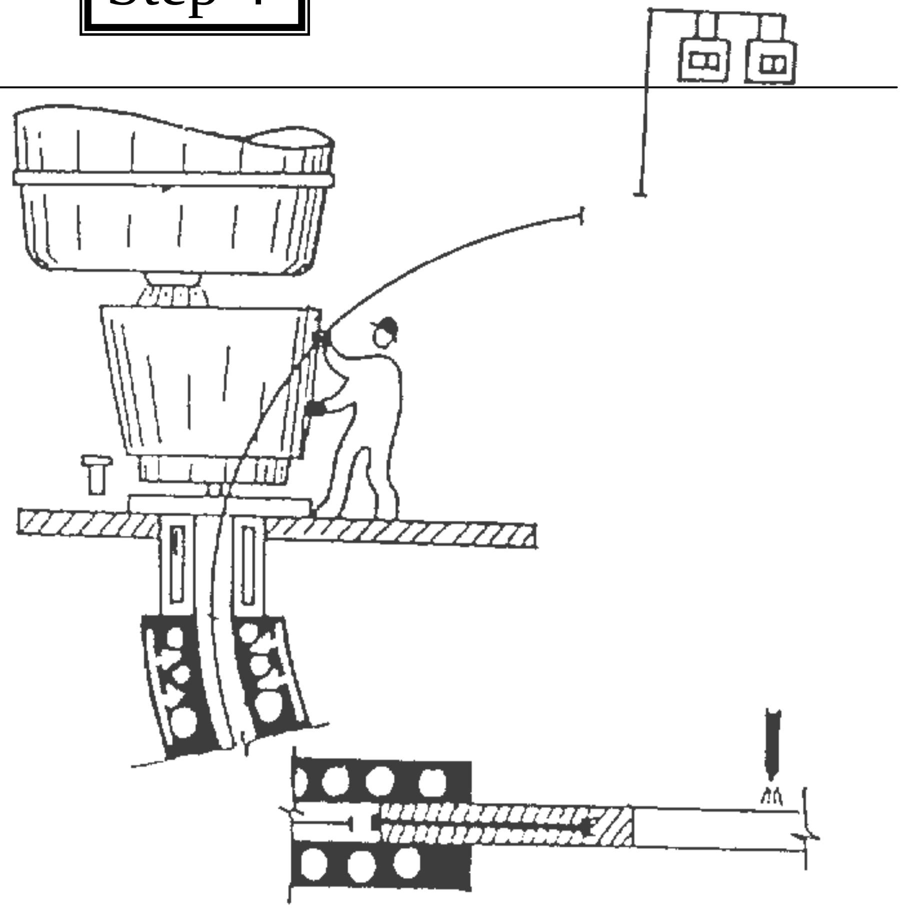


- Let entire block length (~1.8 m) be drawn into slab.

Step 3

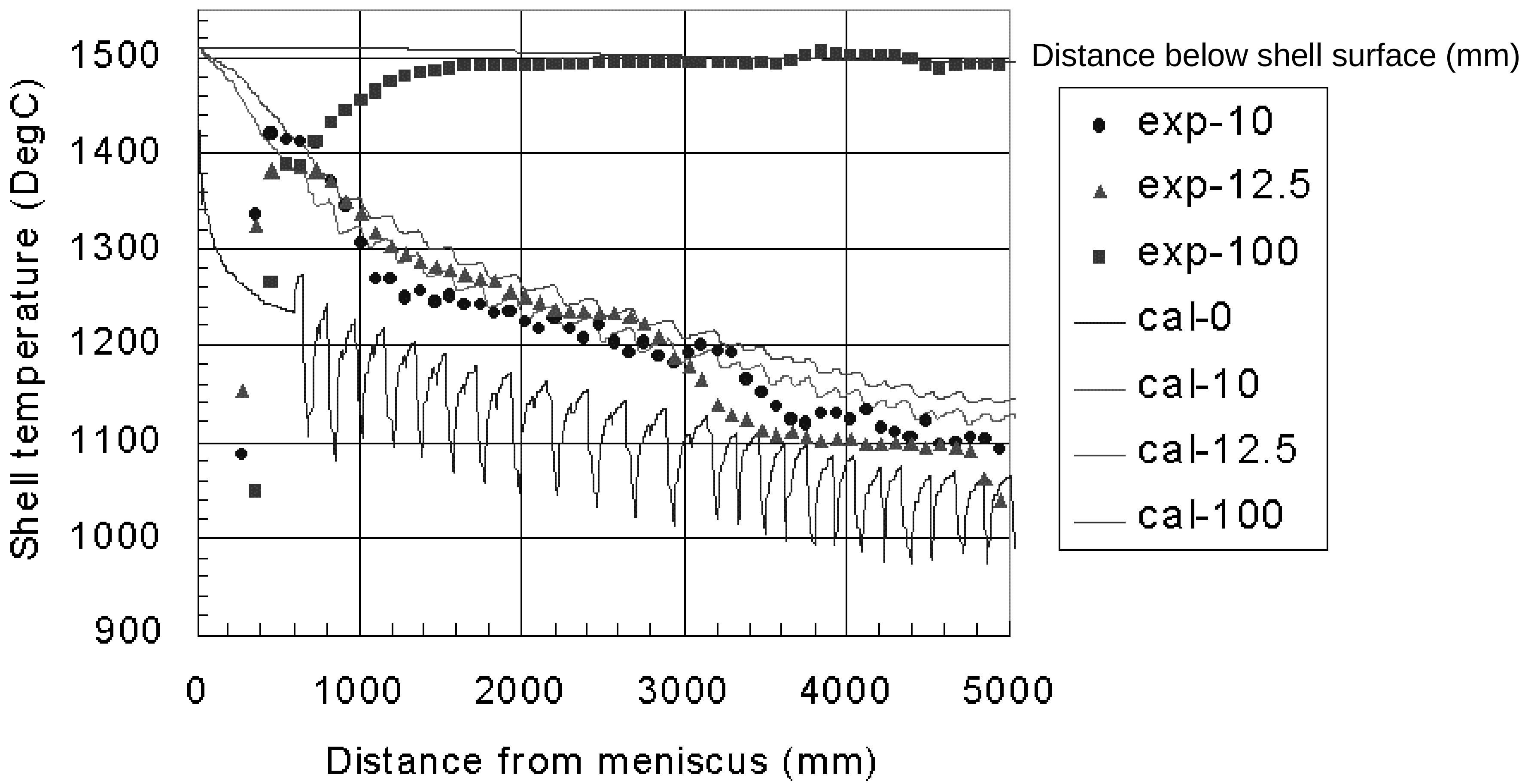


Step 4

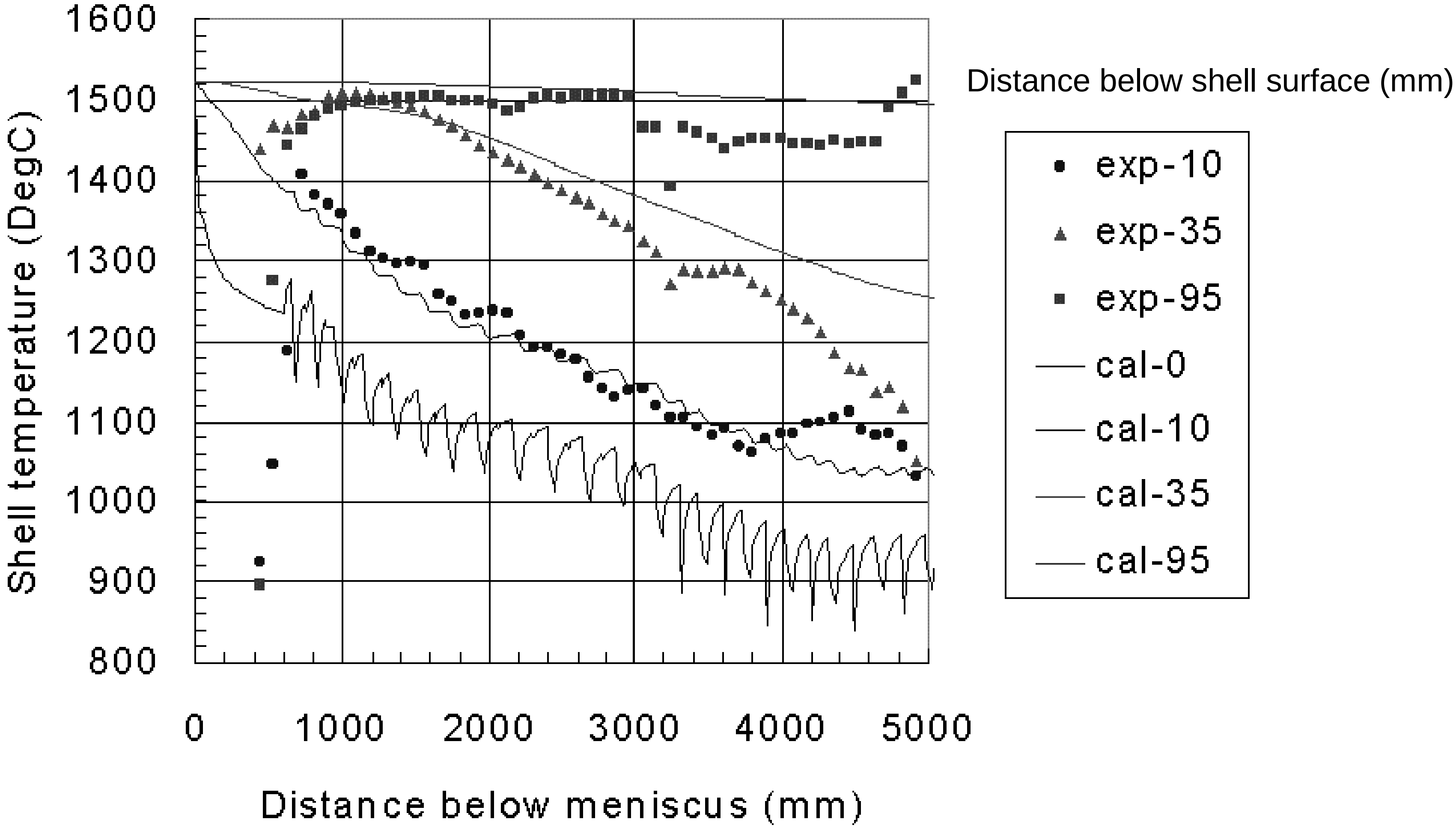


- Close slide gate, while slab with embedded thermocouple block is drawn along at casting speed.
- When slab is horizontal, cut off end (~ 2 m) and measure exact thermocouple positions.

Thermal Model Validation: Water Spray Only (China Steel)



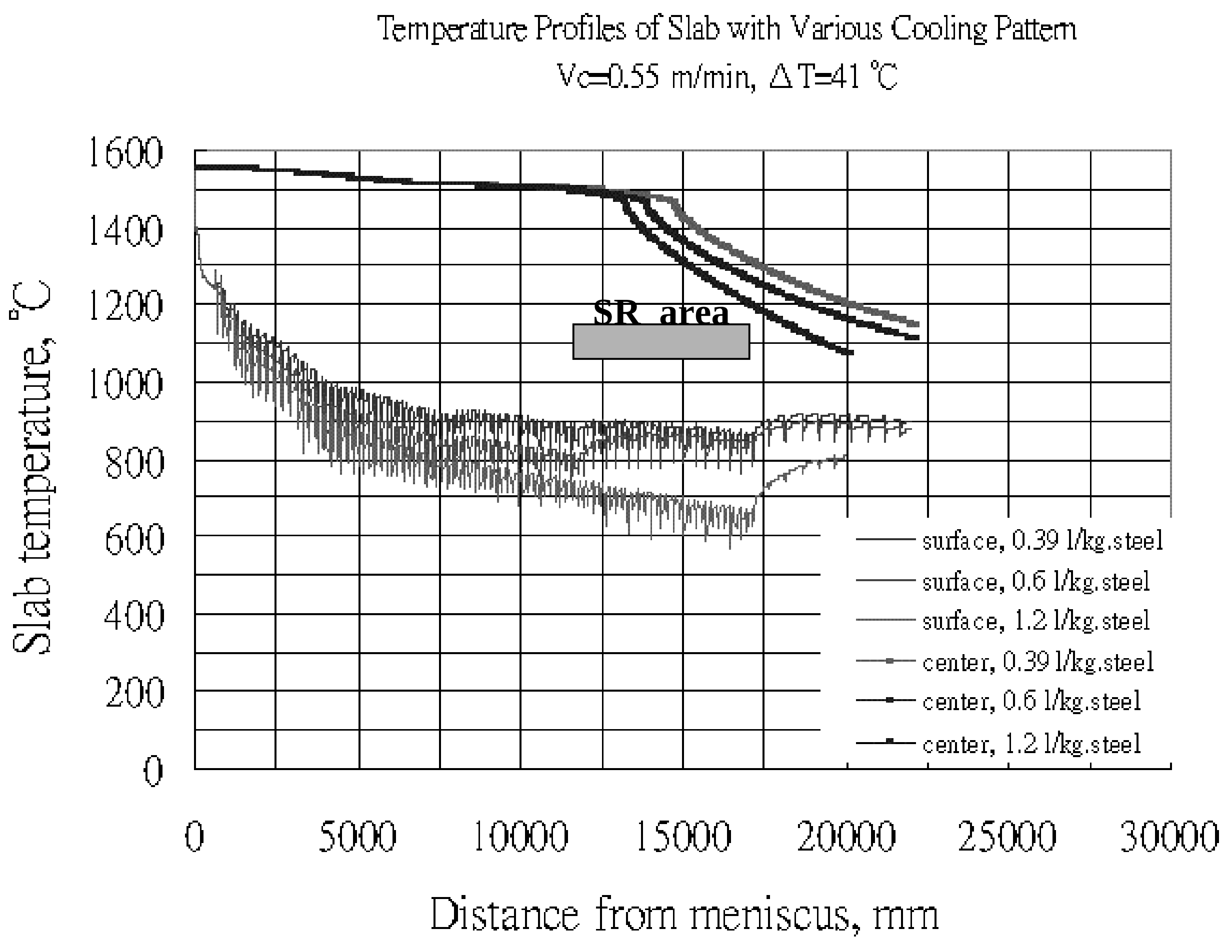
Thermal Model Validation: Air Mist Cooling (China Steel)



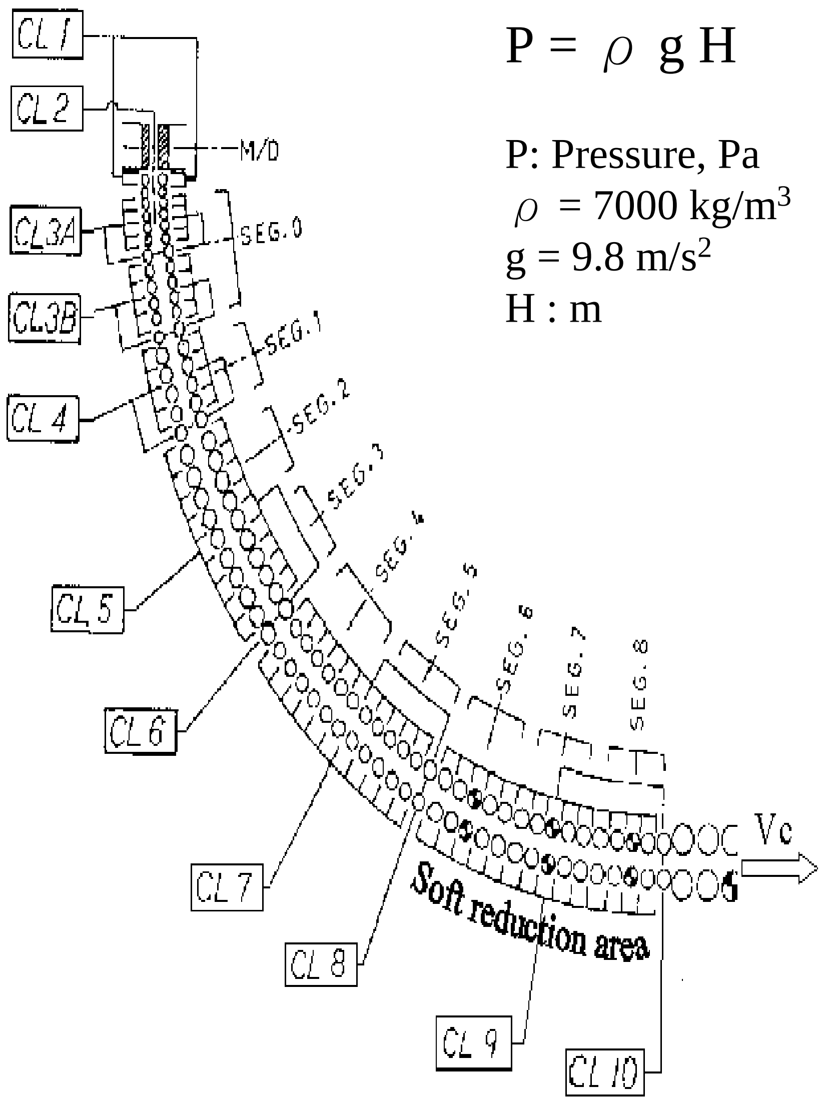
3 Slab Cooling Conditions (#1SCC China Steel)

	Case 1	Case 2	Case 3
Casting Speed: (m/min)	0.55	0.55	0.55
Pour Temperature: (^oC)	1551	1551	1551
Slab Geometry: (mm*mm)	1560*270	1560*270	1560*270
C/Si/Mn/Nb/V/Al content, %	0.16/0.28/1.33/0.023/0.078/0.025		
Water flow rate in spray zone, l/min/row			
Zone 1	19.25	26.5	37.25
Zone 2	9.9	15.4	25.3
Zone 3	8.8	16.0	23.1
Zone 4	9.9	20.1	28.6
Zone 5	8.25	15.4	27.0
Zone 6	8.28	8.75	20.7
Zone 7	2.57	2.57	16.6
Water Intensity, l/kg.steel	0.39	0.60	1.20

Calculated Slab Temperatures



Ferrostatic Pressure along Strand



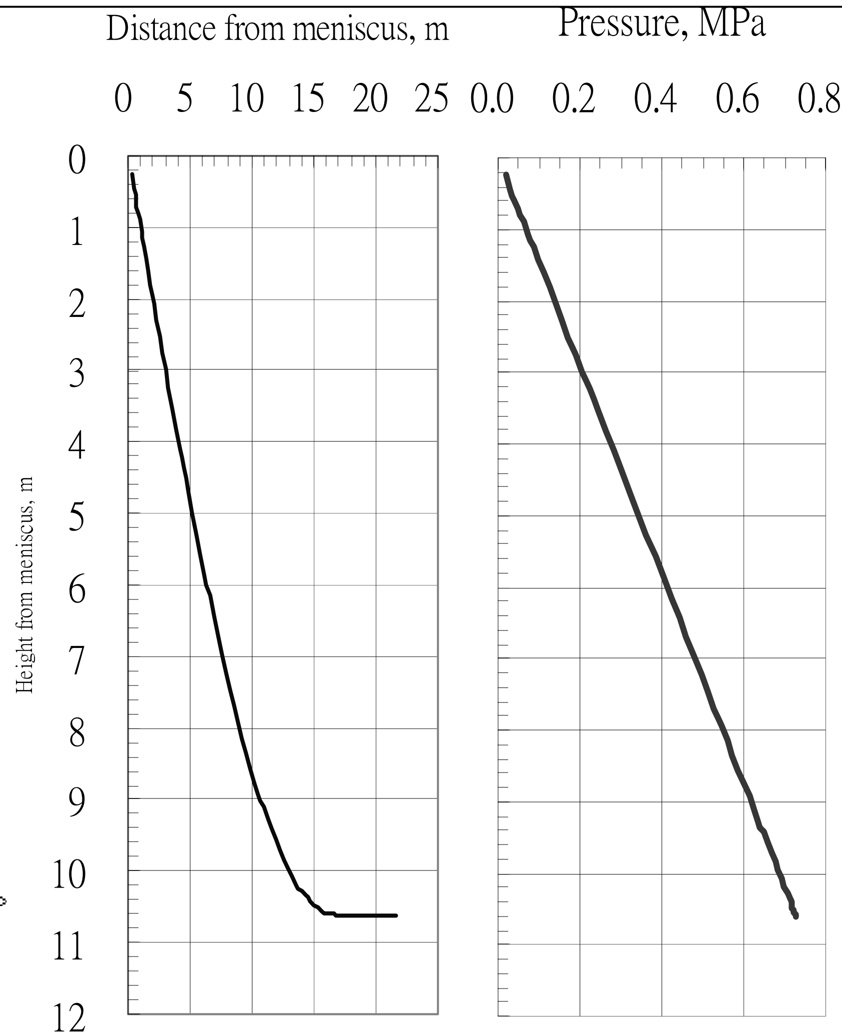
$P = \rho g H$

P: Pressure, Pa

ρ = 7000 kg/m^3

g = 9.8 m/s^2

H : m



#1SCC machine layout

					0.39 l/kg.steel		0.6 l/kg.steel		1.2 l/kg.steel	
Roll No.	Diameter ,mm	roll position ,mm	roll pitch, mm	Avg. pressure between rolls, Pa	Shell thickness, mm	Tsurf., ℃	Shell thickness, mm	Tsurf., ℃	Shell thickness, mm	Tsurf., ℃
1	140	720.1	171.1	55266	21.09	1230.8	21.23	1217.0	21.39	1200.2
2	140	891.2	180.1	67292	22.89	1197.8	23.07	1177.5	23.28	1148.8
3	140	1071.3	181.9	79674	24.73	1169.6	25.18	1145.3	25.87	1109.7
4	140	1253.3	181.9	92098	28.43	1148.2	29.20	1121.1	30.06	1081.6
5	140	1435.2	180.1	104437	31.13	1129.5	31.69	1100.4	32.35	1057.8
6	140	1615.3	208.9	117666	32.87	1112.7	33.39	1081.8	34.04	1036.8
7	200	1824.2	239.6	132871	34.82	1108.8	36.10	1071.0	38.25	1030.9
8	200	2063.8	237.8	148994	39.48	1100.5	41.21	1058.0	42.91	1020.3
9	200	2301.5	239.6	165047	42.88	1088.8	44.12	1043.4	45.26	1005.9
10	200	2541.1	237.8	181021	44.97	1076.9	46.00	1029.1	46.95	991.4
11	200	2778.9	239.6	196906	46.58	1065.2	47.55	1015.5	48.49	977.4
12	200	3018.4	266.6	213643	48.18	1044.3	49.27	991.8	51.24	953.0
13	250	3285.0	300.8	232262	50.49	1008.9	53.51	953.0	56.22	911.7
14	250	3585.8	302.6	251890	55.04	989.7	57.63	931.6	59.33	889.5
15	250	3888.4	300.8	271317	58.34	973.9	60.17	913.1	61.46	871.3
16	250	4189.2	302.6	290526	60.54	959.5	62.08	898.5	63.26	855.9
17	250	4491.8	336.8	310620	62.45	960.0	63.96	896.9	66.33	849.9
18	300	4828.6	340.4	331602	64.47	955.7	68.57	891.7	72.47	841.7
19	300	5169.0	340.4	352354	69.30	947.6	73.80	883.0	76.27	830.9
20	300	5509.4	342.2	372795	73.80	939.0	76.89	874.1	78.70	820.7
21	300	5851.7	340.4	392848	76.67	930.6	79.05	865.1	80.57	811.4
22	300	6192.1	340.4	412438	78.77	922.4	80.82	855.4	82.24	802.0
23	300	6532.5	353.0	431945	80.49	914.4	82.43	846.6	83.93	793.4
24	300	6885.5	340.4	450991	82.06	906.5	84.07	838.5	87.94	785.8
25	300	7226.0	340.4	469211	83.62	898.9	88.15	830.8	93.87	777.8

#1SCC machine layout, cntd

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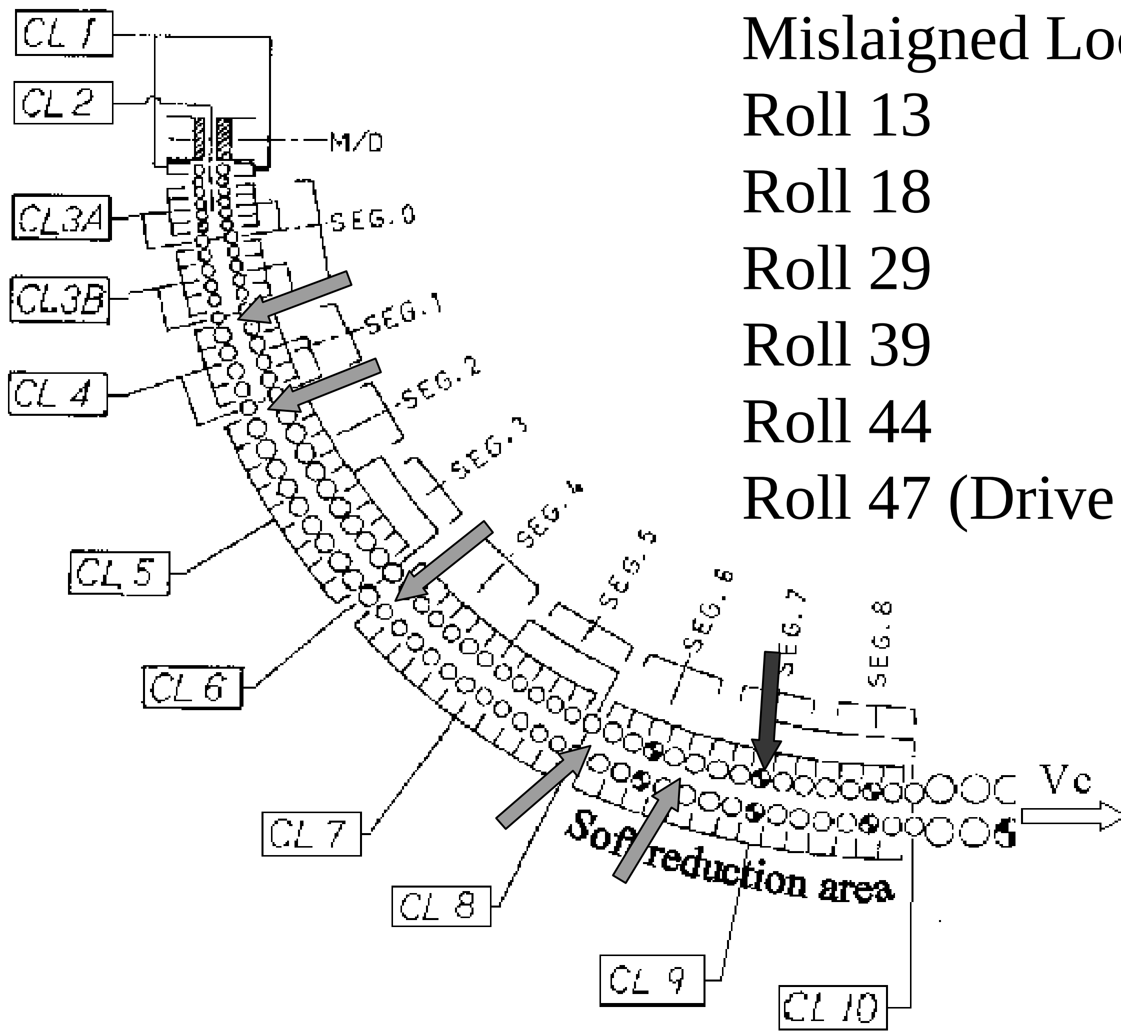
Roll No.	Diameter, mm	roll position, mm	roll pitch, mm	Avg. pressure between rolls, Pa	0.39 l/kg.steel Shell thickness, mm	0.39 l/kg.steel Tsurf., ℃	0.6 l/kg.steel Shell thickness, mm	0.6 l/kg.steel Tsurf., ℃	1.2 l/kg.steel Shell thickness, mm	1.2 l/kg.steel Tsurf., ℃
26	300	7566.4	342.2	486985	86.27	891.5	93.67	823.8	97.74	770.7
27	300	7908.6	338.6	504202	91.48	900.2	97.36	831.4	100.30	770.4
28	280	8247.2	329.6	520587	95.49	902.7	99.86	832.1	102.21	766.2
29	280	8576.9	329.6	536231	98.29	901.2	101.77	829.3	103.79	761.3
30	280	8906.5	329.6	551346	100.37	898.5	103.34	825.6	105.18	756.2
31	280	9236.1	329.6	565916	102.05	895.3	104.72	821.7	106.51	751.4
32	280	9565.7	329.6	579926	103.49	891.7	106.02	817.7	107.84	747.1
33	280	9895.3	336.8	593502	104.80	887.8	107.29	813.7	109.23	742.5
34	280	10232.1	329.6	606484	106.05	883.9	108.60	809.6	112.93	738.0
35	280	10561.8	329.6	618718	107.28	879.9	110.57	805.6	118.29	733.3
36	280	10891.4	327.8	630308	108.54	876.0	115.54	801.8	122.53	728.8
37	280	11219.2	329.6	641275	110.17	872.0	120.06	798.0	125.67	724.4
38	280	11548.8	329.6	651636	114.58	868.2	123.68	794.8	128.30	720.6
39	280	11878.4	351.2	661647	119.08	879.8	126.60	822.0	130.70	718.6
40	310	12229.6	347.6	671207	122.99	880.7	129.22	835.6	133.10	709.8
41	310	12577.3	347.6	679971	126.07	880.9	131.62	841.8	133.76	704.0
42	310	12924.9	347.6	687983	128.71	879.9	133.70	845.1	133.76	698.6
43	310	13272.5	347.6	695235	131.11	878.1	133.70	846.8	133.76	694.2
44	310	13620.2	354.8	701775	133.46	876.3	133.70	847.5	133.76	689.8
45	310	13975.0	346.7	707525	133.82	874.3	133.70	847.5	133.76	685.1
46	310	14321.7	348.2	712447	133.82	871.9	133.70	846.6	133.76	679.9

Detailed bulging analysis (both pressure and misalignment)



Mislaigned Locations:
Roll 13
Roll 18
Roll 29
Roll 39
Roll 44
Roll 47 (Drive Roll)

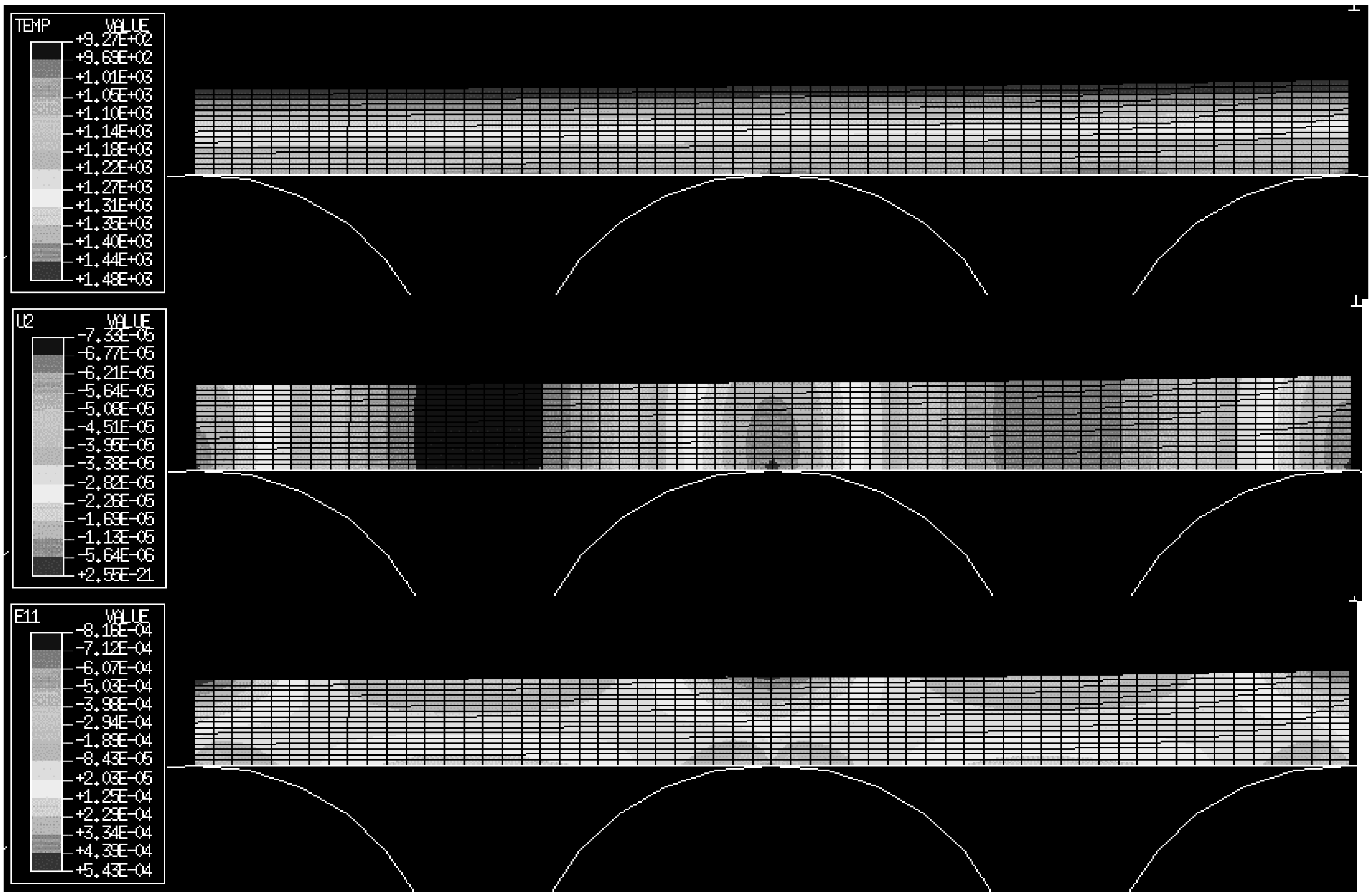
ABAQUS Results: Rolls 12 - 14 (Spray Case 1)

Rolls 12-14   Cooling: 0.39 l/kg.steel, 0.55 m/min P=0.21-0.24 MPa, Shell=47.3-52.8 mm

Temp (C)

Displ. (m)

Strain (-)



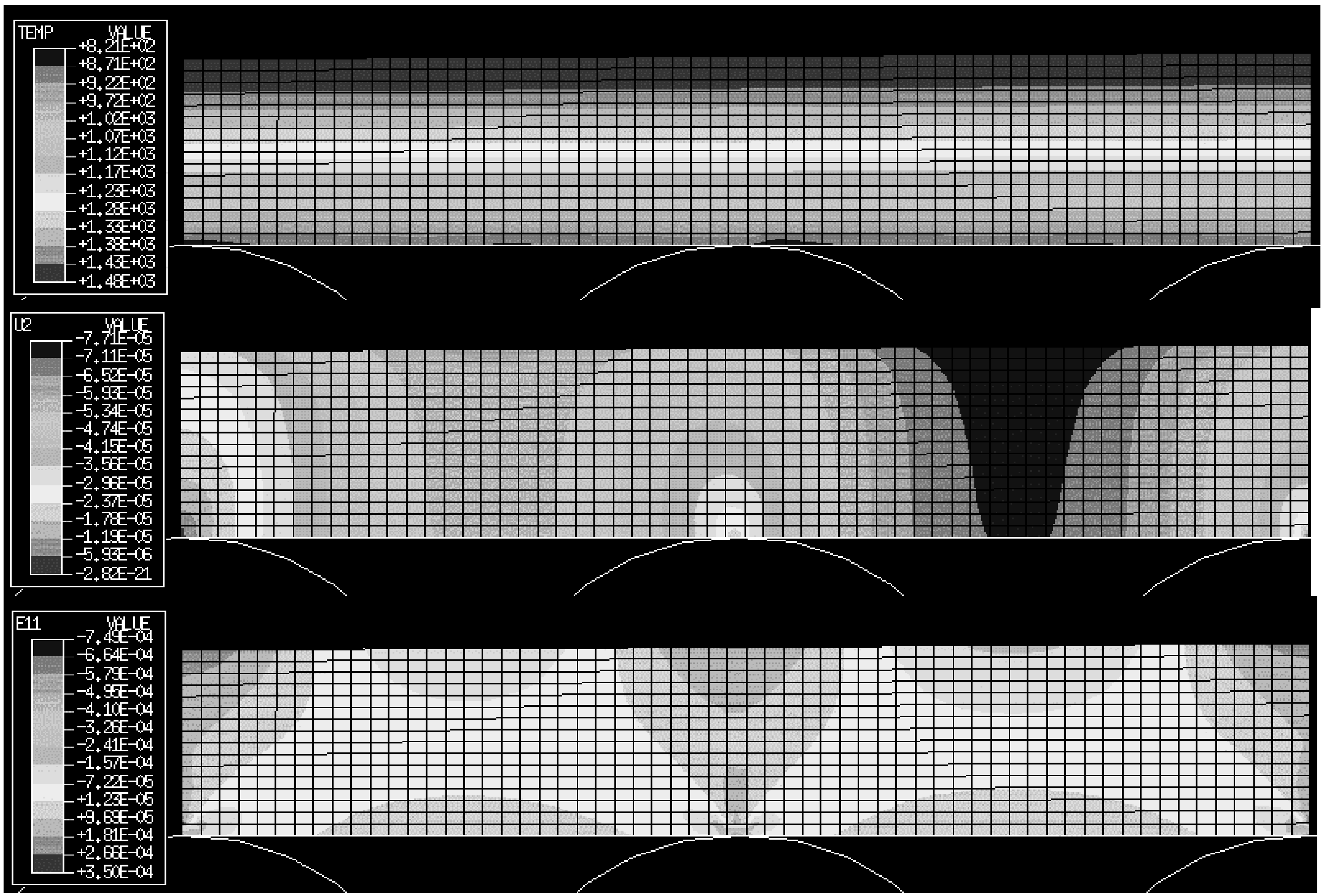
ABAQUS Results: Rolls 43-45 (Spray Case 1)

Rolls 43-45   0.55 m/min Spray Cooling Case 1: 0.39 l/kg.steel, P=0.69-0.70 MPa, Shell=129.9-134.5 mm

Temp (C)

Displ. (m)

Strain (-)

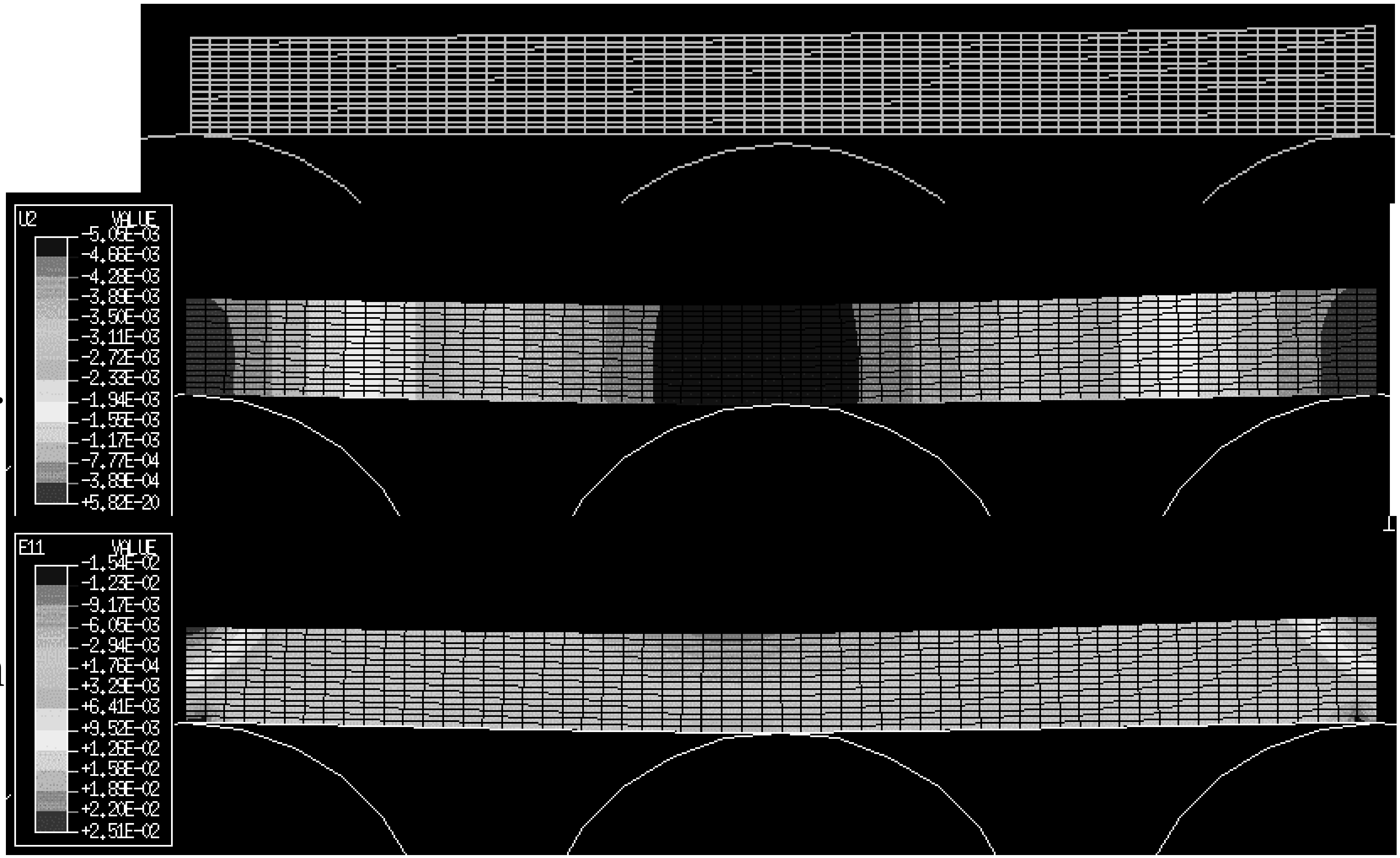


ABAQUS Results: Roll 13 misaligned 5mm

Rolls 12-14 Cooling: 0.39 l/kg.steel, 0.55 m/min P=0.21-0.24 MPa, Shell=47.3-52.8 mm

Displ. (m)

Strain (-)

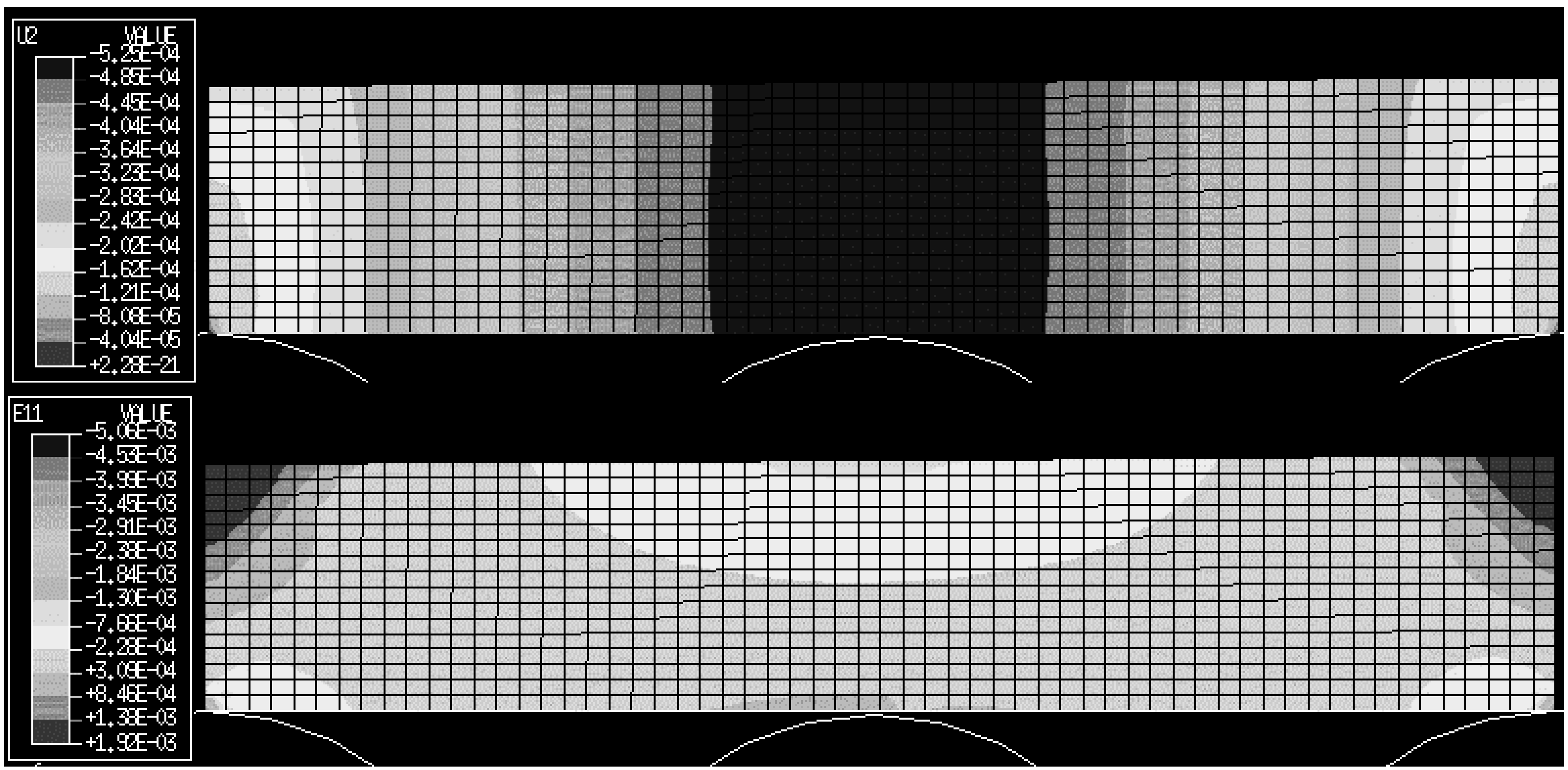


ABAQUS Results: Roll 44 misaligned 2mm

Rolls 43-45   0.55 m/min Spray Cooling Case 1: 0.39 l/kg.steel, P=0.69-0.70 MPa, Shell=129.9-134.5 mm

Displ. (m)

Strain (-)



Validation Experiment: Displacement of drive roll no.47

Casting condition:

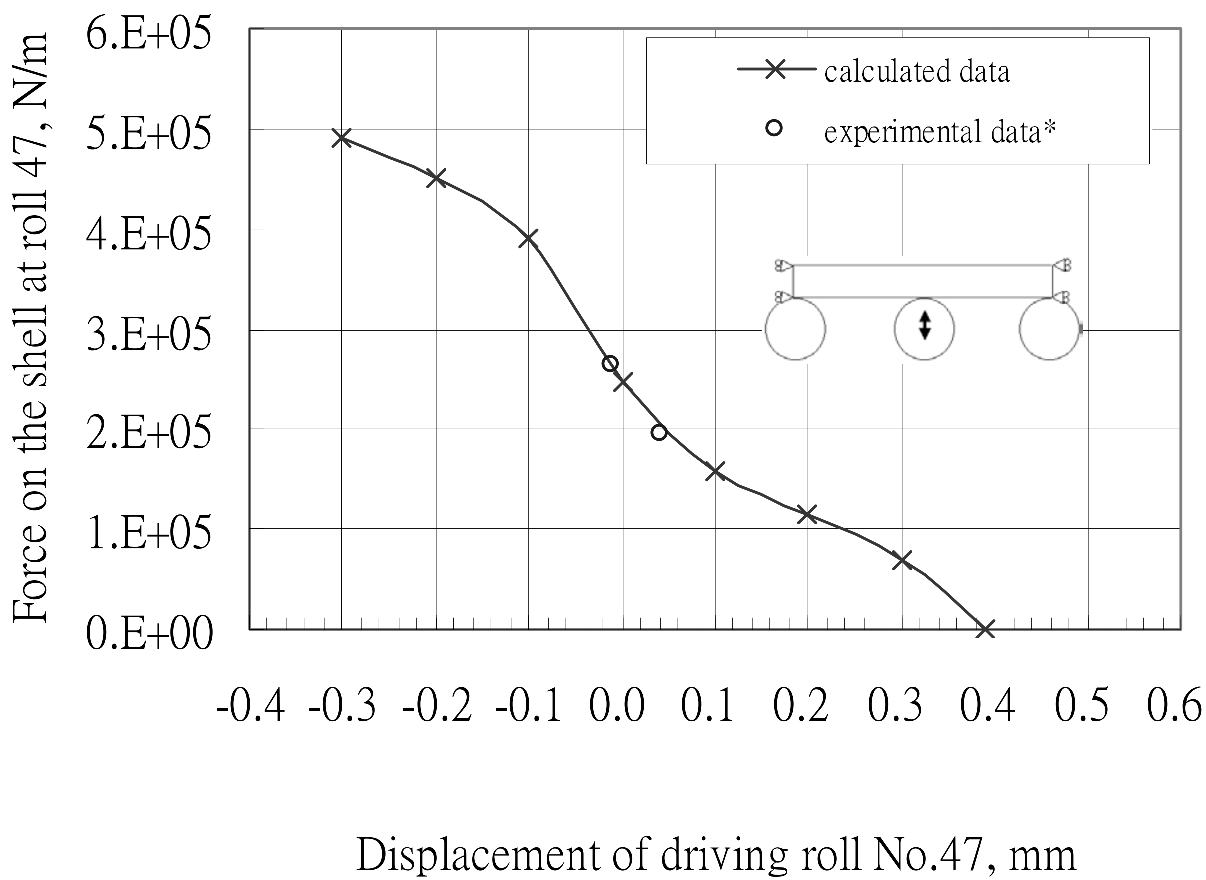
*Vc = 0.6 m/min
*Cooling intensity: 0.39 l/kg.steel
*Shell thickness: 129.9 - 134.2 mm
*Pressure: 0.71 - 0.72 MPa

Measured displacement of the driving roll :

Oil pressure of roll on shell	Relative displacement*, mm
80 kg/cm^2	0.0
59.5 kg/cm^2	0.05

* the relative displacement is based on the position when pressure is 80 kg/cm^2

Relationship between Drive Roll Displacement and Oil Pressure



* experimental displacements not measured, so are assumed to match calculations

Spray cooling effect on bulging & strain from roll misalignment

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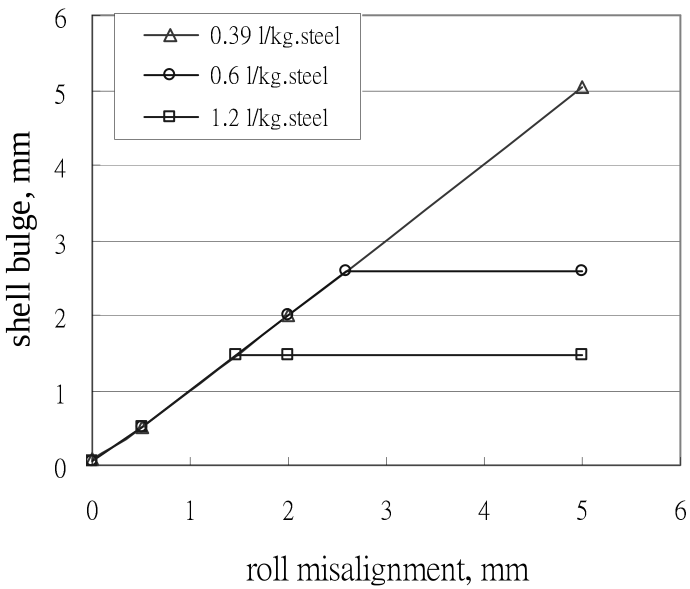
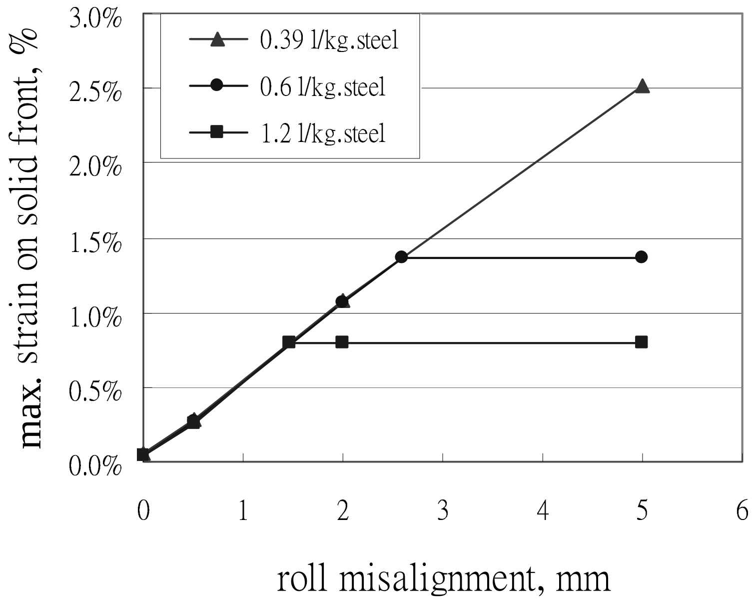
Rolls 12-14   0.55 m/min P=0.21-0.24 MPa

Cooling pattern	0.39 l/kg.steel	0.6 l/kg.steel	1.2 l/kg.steel
Shell thickness, mm	47.3 – 52.8	48.3 – 56.0	49.3 – 58.0
Slab surface Temp. ℃	990 -1070	920 - 1030	860 - 1000
[illegible]	[illegible]	[illegible]	[illegible]

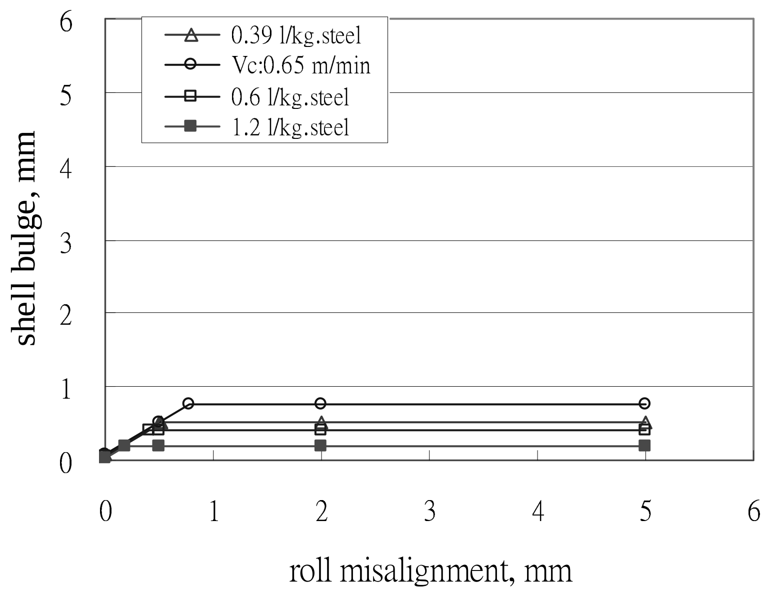


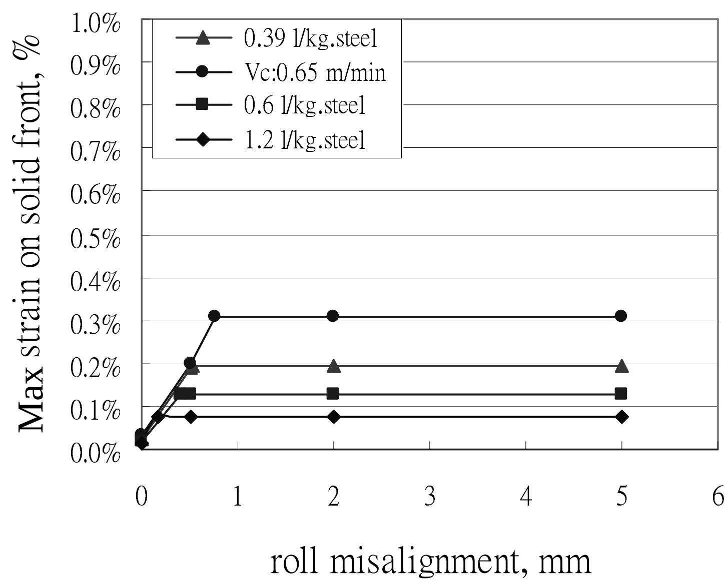


Spray cooling effect on bulging & strain from roll misalignment

Rolls 43-45   0.55 m/min P=0.69-0.70 MPa

Cooling pattern	0.39 l/kg.steel	0.6 l/kg.steel	1.2 l/kg.steel
Shell thickness, mm	129.9 – 134.5	135	135
Slab surface Temp. ℃	808 - 896	784 - 863	617 - 720

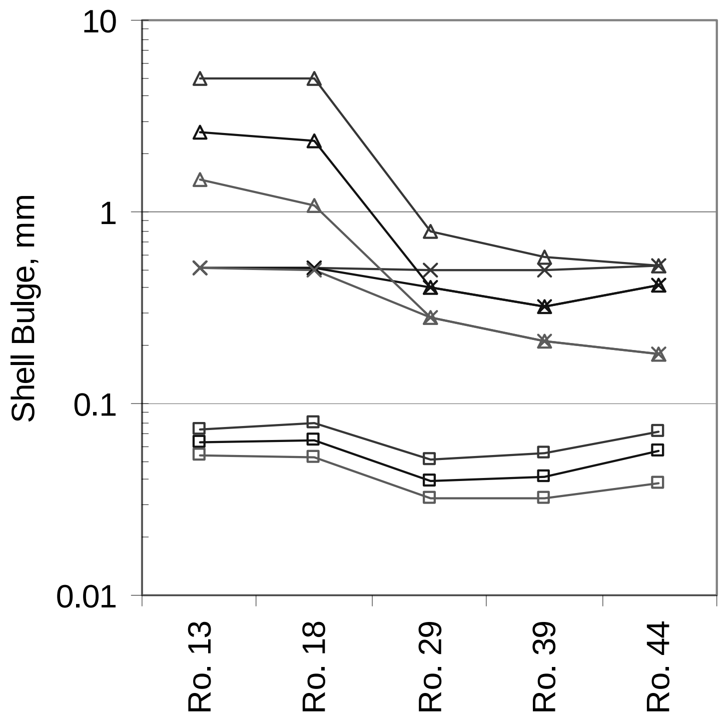


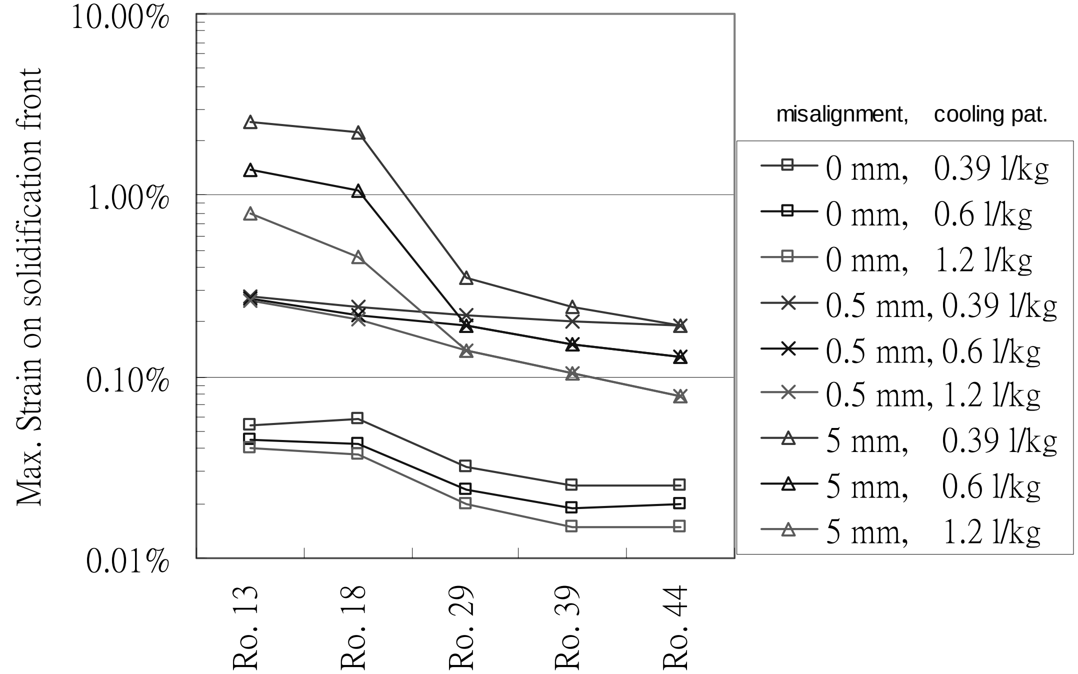


Bulging Misalignment Study: Results Summary

Effect of:
- roll misalignment
- spray cooling intensity
- position down caster

On:
- max. shell bulging
- max. strain on sol. front

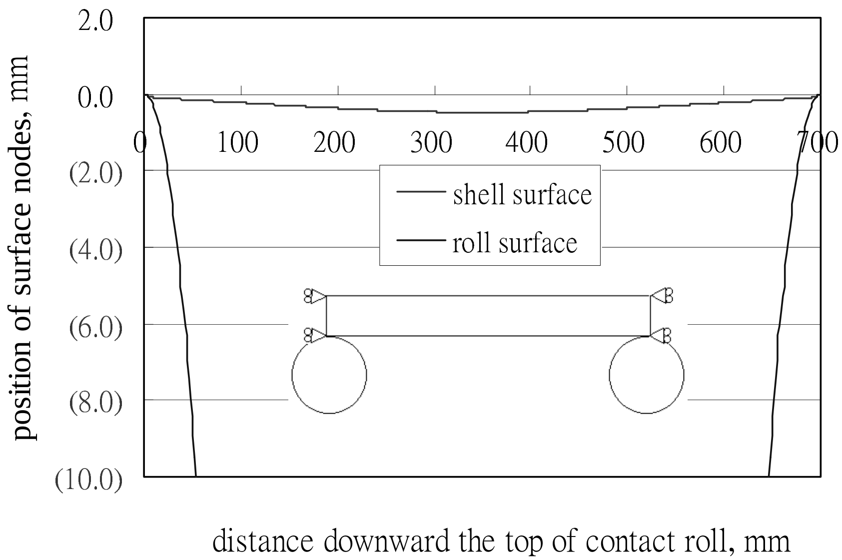


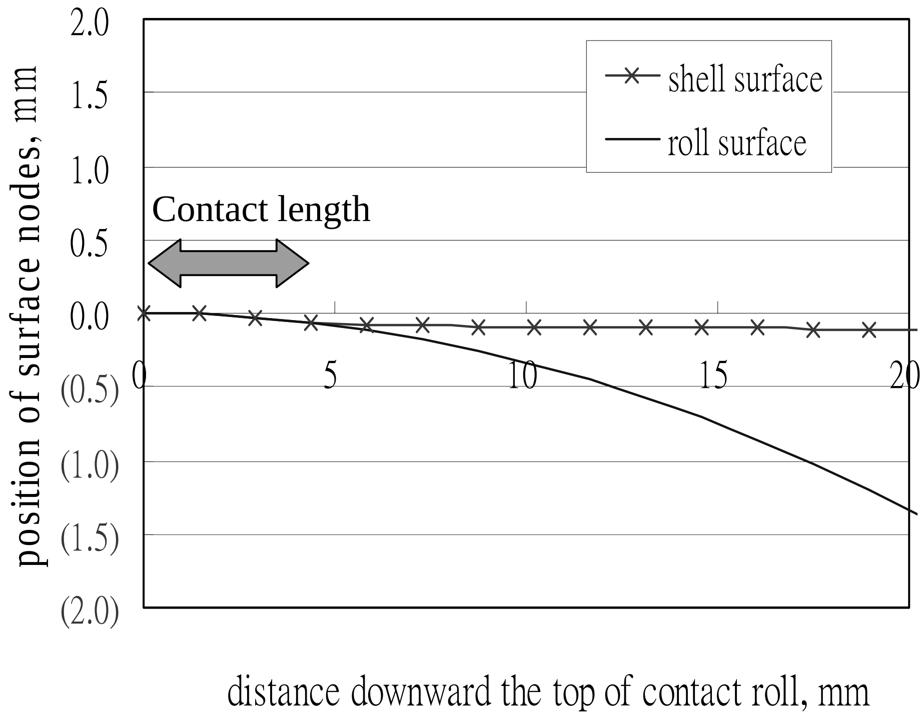


Bulging misalignment study: conclusions

- Roll misalignment is a significant contributor to severe bulging, which will induce fluid flow during final stages of solidification, causing segregation and quality problems
- Shell bulging is negligible (< 0.1mm) when no roll misalignment exists.
- Increasing cooling intensity lowers shell temperature and increases strength. This lowers max. bulging slightly, especially for severe misalignment
- Reducing misalignment should be more effective at lowering bulging than increasing cooling

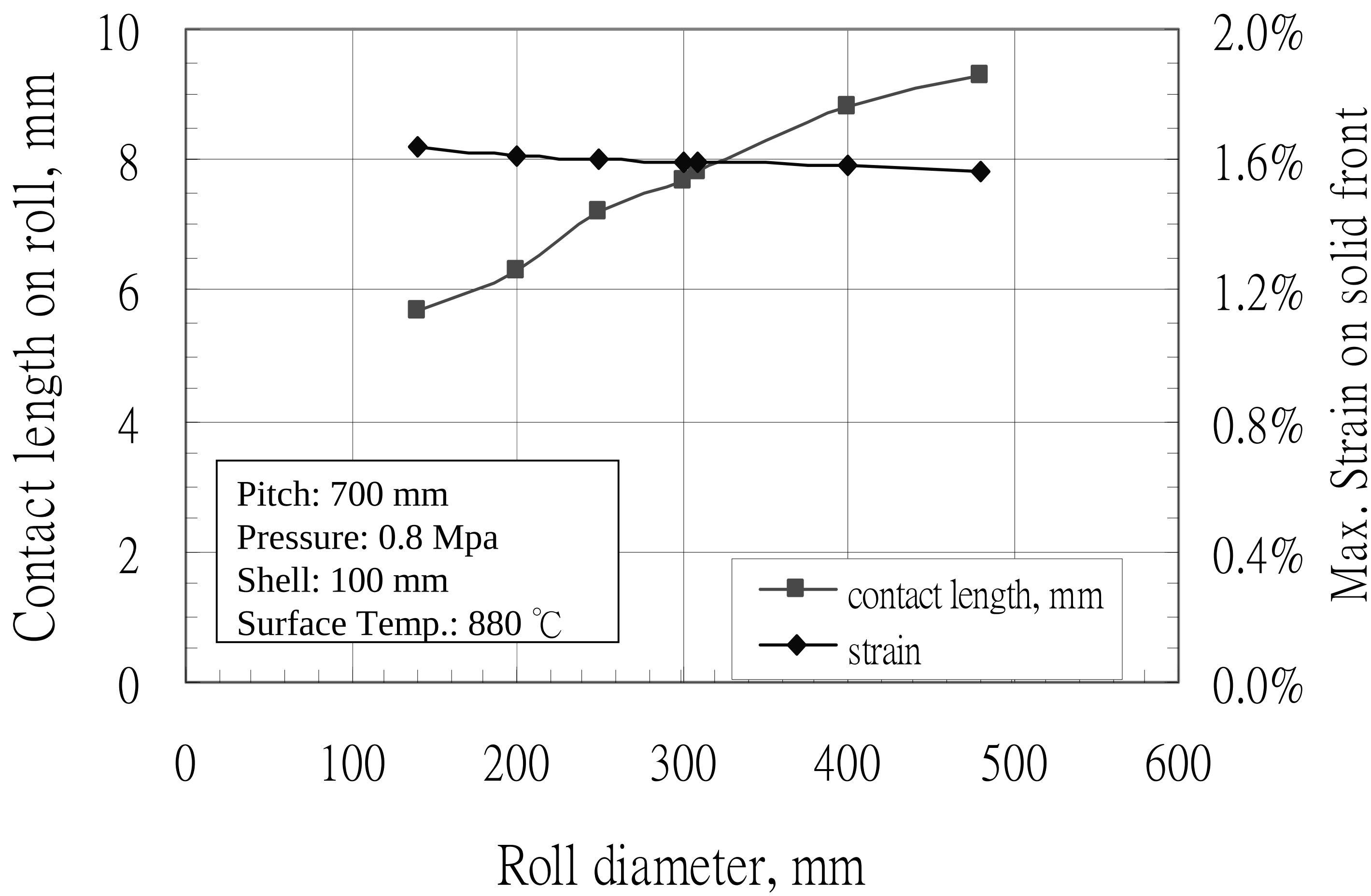
Study of support roll surface – steel shell contact





Roll pitch: 700 mm
Shell thickness: 130 mm
Pressure: 0.7 MPa
Shell temperature: 880 ℃
Roll Diameter: 300 mm
Max. shell bulge: 0.47 mm

Effect of support roll diameter on shell contact length

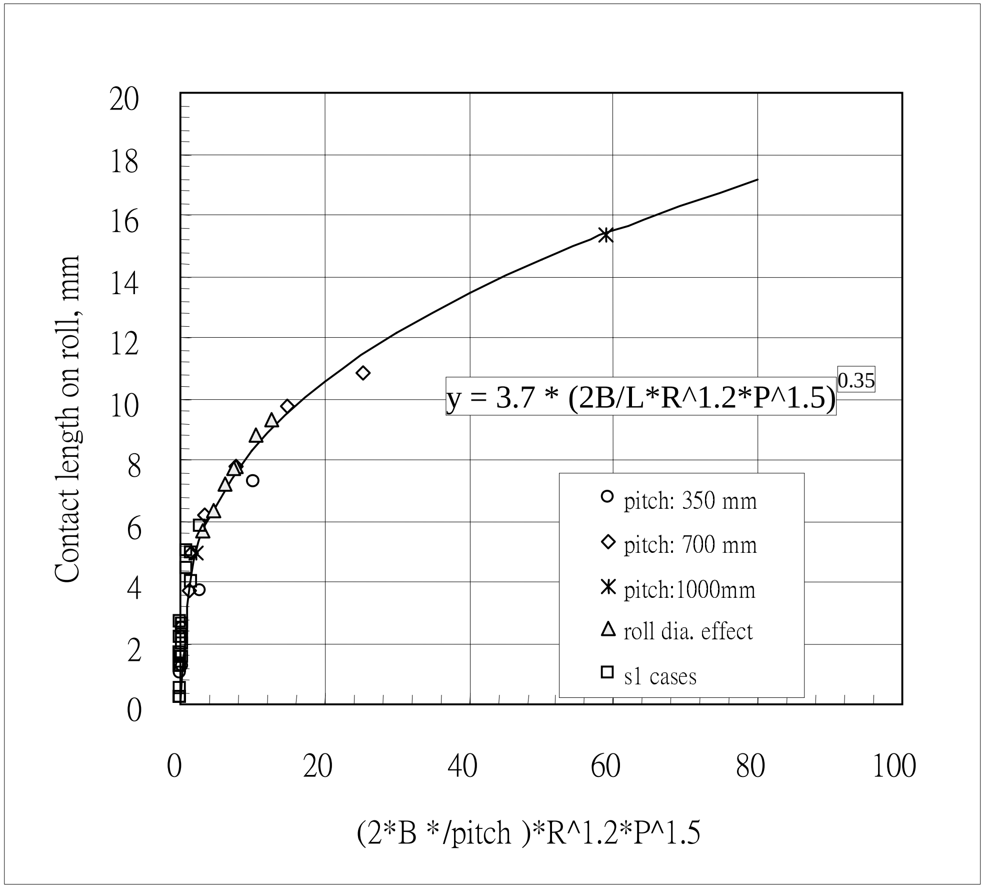


Conditions of roll contact parametric study

pitch,mm	pitch/2, mm	shell, mm	Pressure, Mpa	Tsurf, ℃	Roll Dia, mm
350	175	30	0.1	880	310
350	175	30	0.2	880	310
350	175	30	0.3	880	310
350	175	30	0.4	880	310
350	175	100	0.8	880	310
700	350	30	0.1	880	310
700	350	100	0.6	880	310
700	350	100	0.7	880	310
700	350	100	0.8	880	310
700	350	100	0.9	880	310
700	350	100	1.0	880	310
1000	500	30	0.1	880	310
1000	500	100	0.8	880	310
700	350	100	0.8	880	480
700	350	100	0.8	880	400
700	350	100	0.8	880	310
700	350	100	0.8	880	300
700	350	100	0.8	880	250
700	350	100	0.8	880	200
700	350	100	0.8	880	140

pitch,mm	pitch/2, mm	shell,mm	Pressure, Mpa	Tsurf, C	Roll Dia,mm	remarks
184	92	25	0.06	1170	140	
184	92	25	0.08	1170	140	roll 3
184	92	25	0.1	1170	140	
368	184	25	0.08	1170	140	
244	122	40	0.12	1100	200	
244	122	40	0.15	1100	200	roll 8
244	122	40	0.18	1100	200	
488	244	40	0.15	1100	200	
310	155	55	0.22	990	250	
310	155	55	0.25	990	250	roll 14
310	155	55	0.28	990	250	
620	310	55	0.25	990	250	
350	175	70	0.3	948	300	
350	175	70	0.35	948	300	roll 19
350	175	70	0.4	948	300	
700	350	70	0.35	948	300	
350	175	86	0.44	891	300	
350	175	86	0.49	891	300	roll 26
350	175	86	0.54	891	300	
700	350	86	0.49	891	300	
340	170	105	0.54	888	300	
340	170	105	0.59	888	300	roll 33
340	170	105	0.64	888	300	
680	340	105	0.59	888	300	
354	177	129	0.64	880	300	
354	177	129	0.69	880	300	roll 42
354	177	129	0.74	880	300	
708	354	129	0.69	880	300	

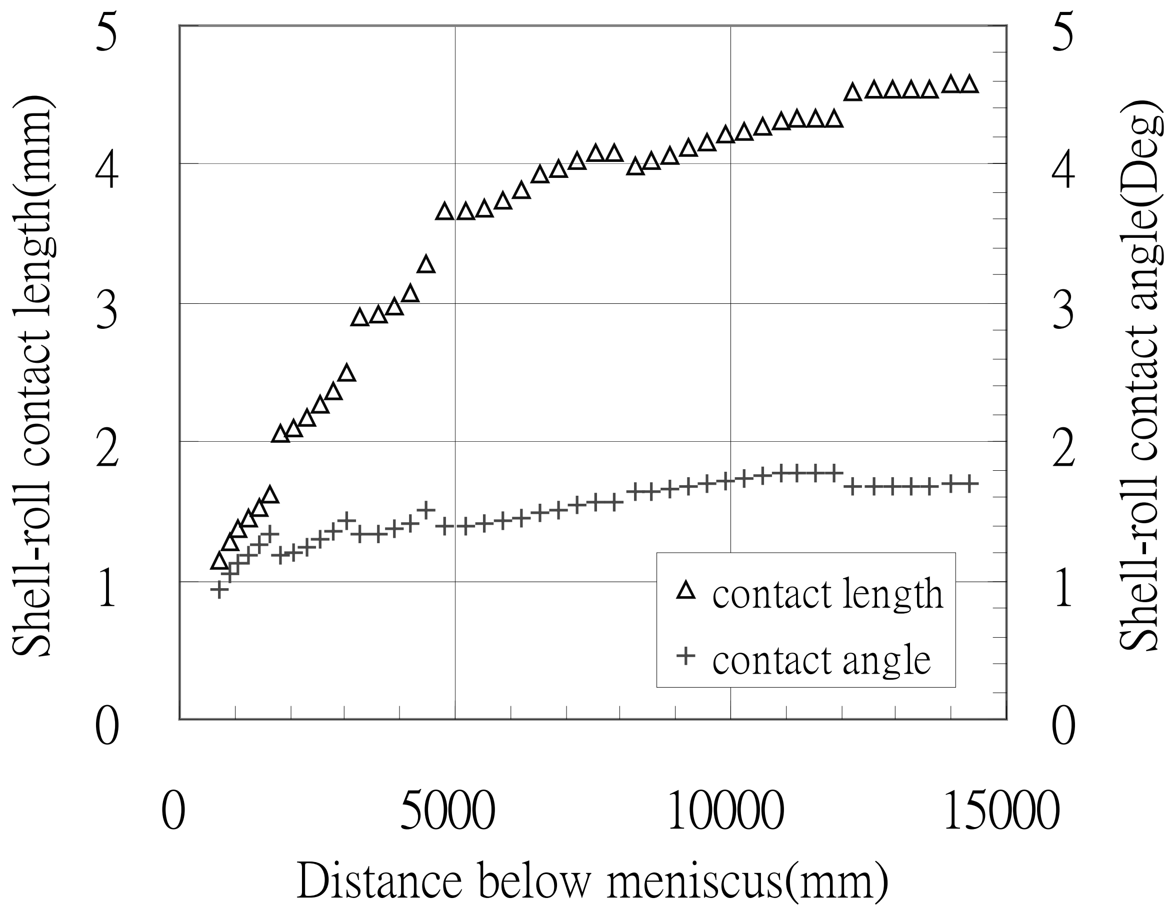
Contact length along roll for different casting conditions



Y = contact length (mm)
B = max. bulge (mm)
L = roll pitch (mm)
R = roll radius (mm)
P = pressure (MPa)

$$Y = 9.432\ B^{0.35} L^{-0.35} R^{0.42} P^{0.525}$$

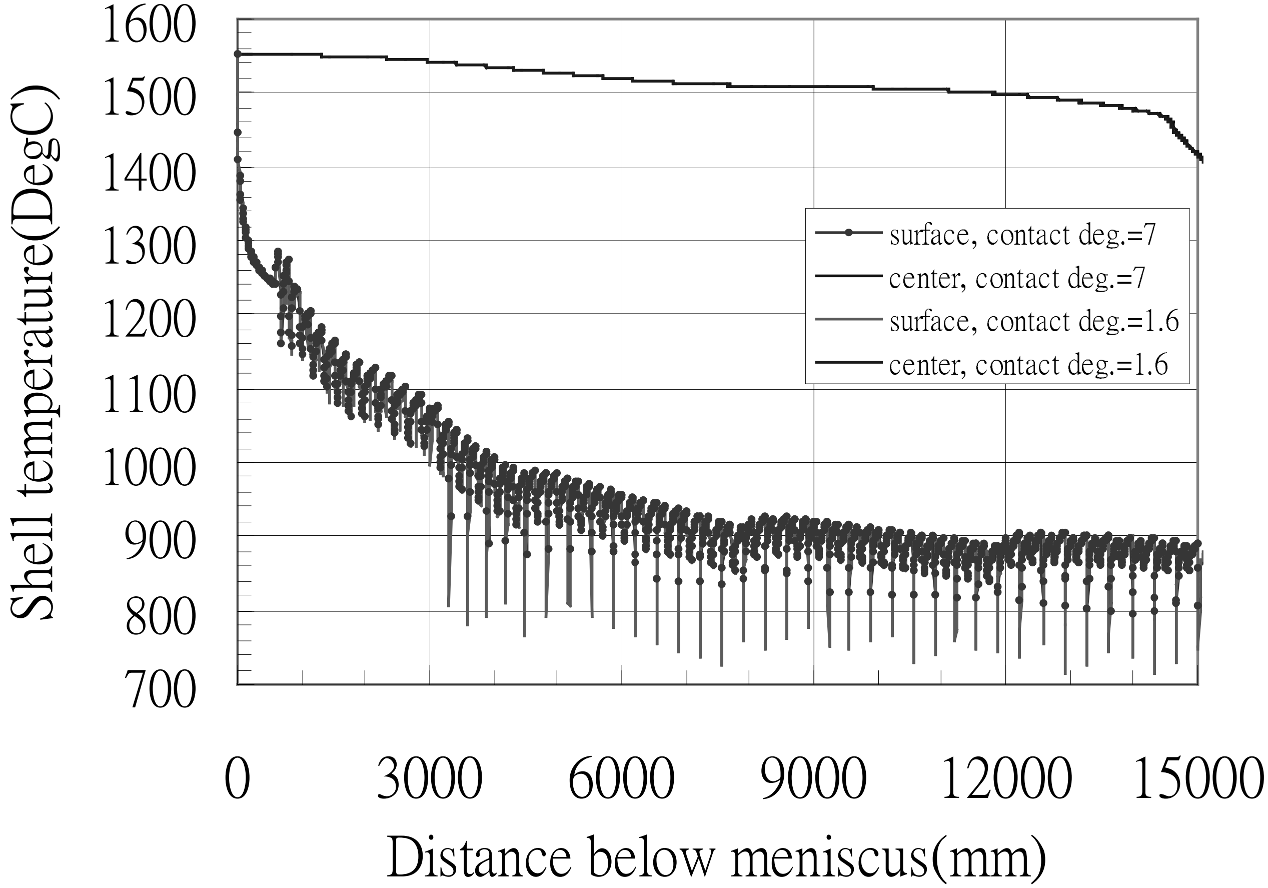
Contact length profile along caster (#1SCC)



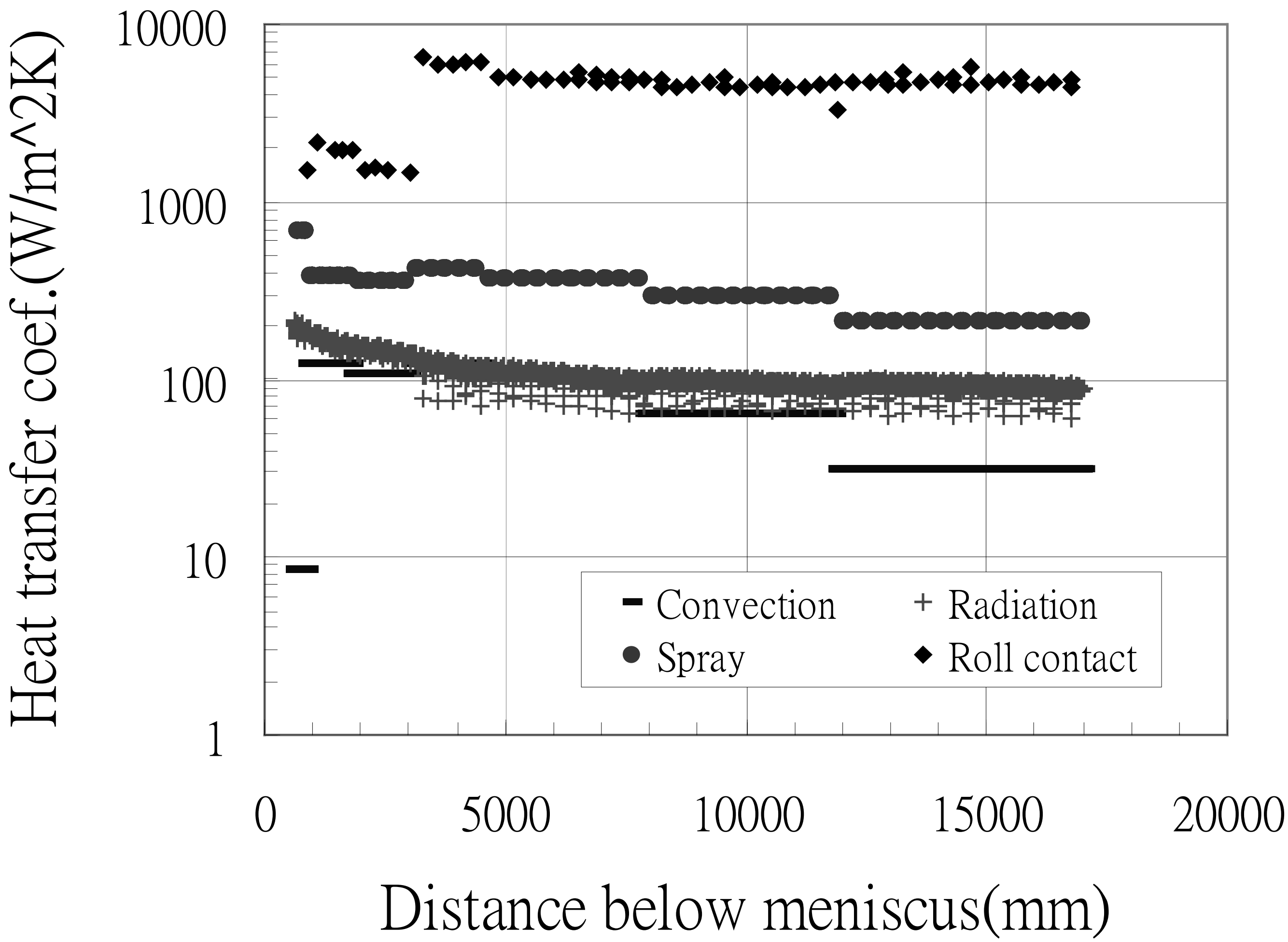
Contact angle generally constant at 1.6 deg.

Effect of roll contact angle on shell surface temp. fluctuations

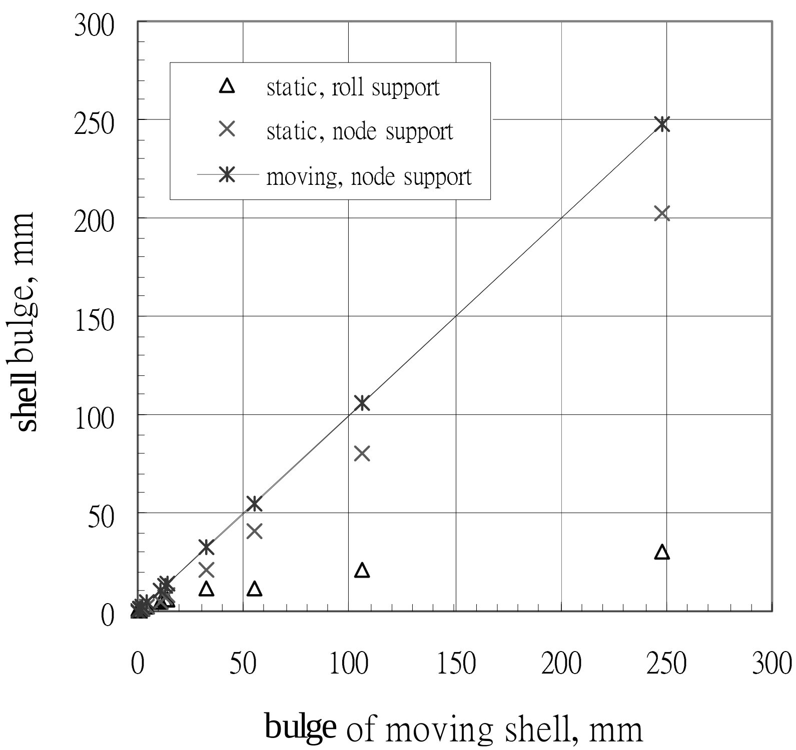
(Vc=0.55 m/min, Cooling Intensity= 0.39 l/kg)

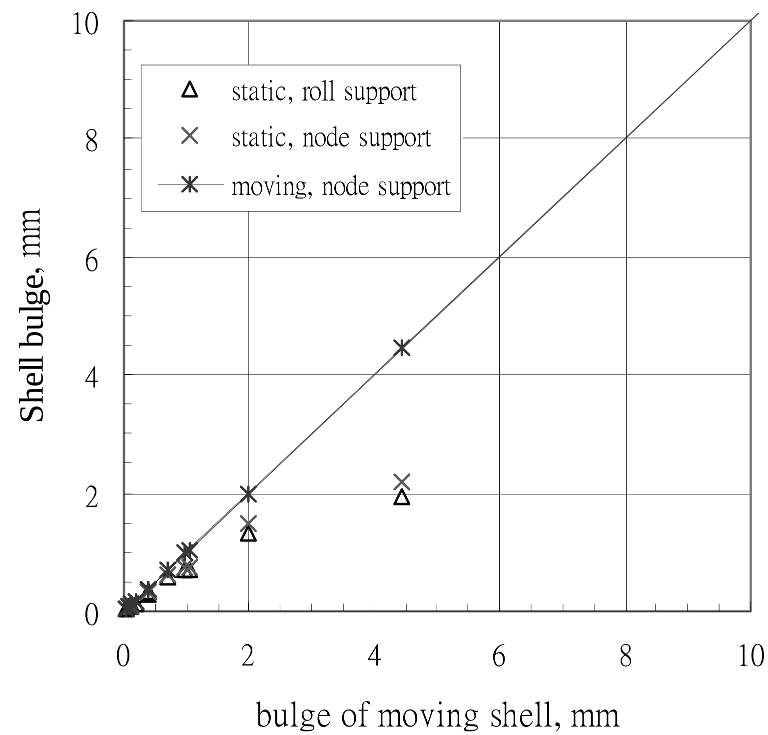


Strand surface heat transfer coefs.



Comparison of bulging from static and moving models



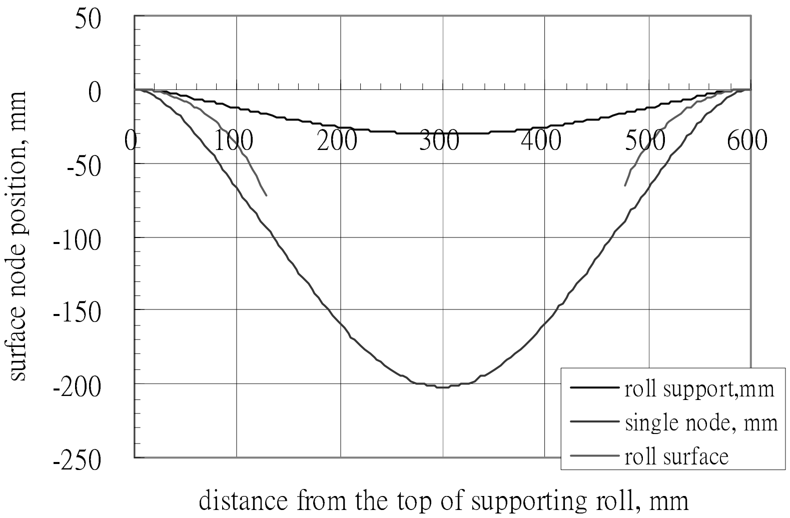


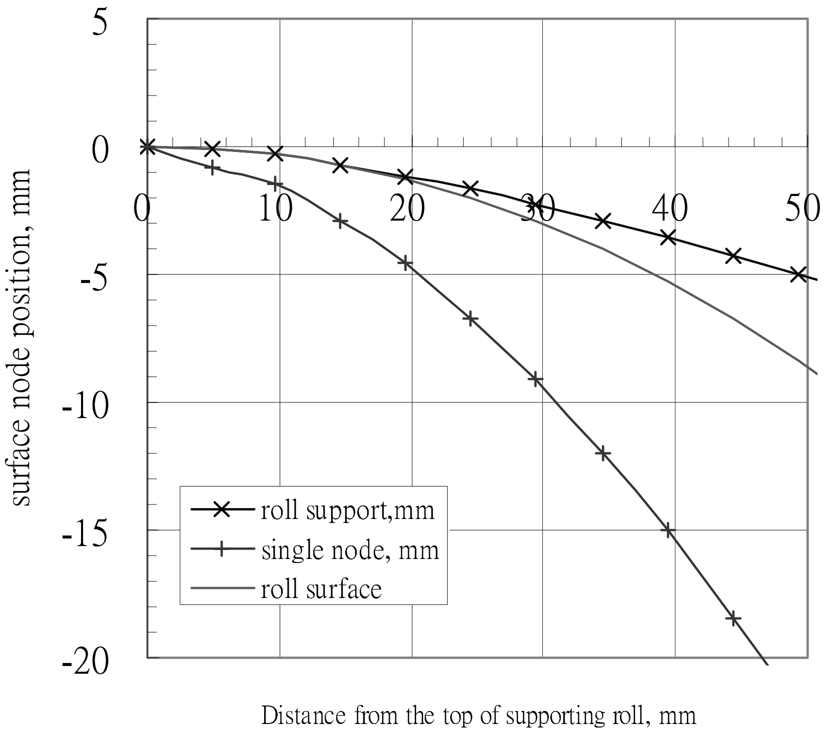
-Moving shell predicts greater bulging than static method

-Difference between methods is small if bulge < 1 mm.

Effect of support from roll curvature on bulging

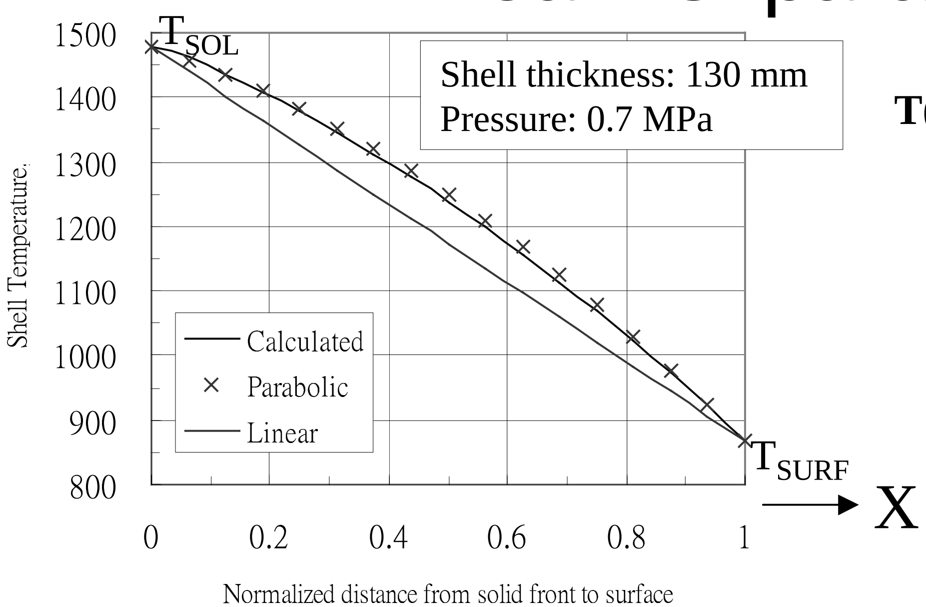
L = 600 mm
P = 0.26 MPa
D = 23.17 mm
Ts = 1000 ℃





Shell Temperature Profile: Effect on Bulging

linear vs. parabolic (actual)



$$T(X) = T_{SOL} + aX + aX^2$$

$a = (T_{SUR} - T_{SOL})/2$

T_{SUR}: Shell surface temperature

T_{SOL}: Solidification temperature at Fs= 0.7

X : Normalized distance from sol. front

Roll Pitch, mm	250	350	500	700	999
Bulging by con1d Temp.(Bo), mm	0.04	0.077	0.177	0.519	7.657
Bulging by Parabolic eq.(Bp), mm	0.04	0.077	0.175	0.502	7.07
Bulging by linear eq.(Bl), mm	0.038	0.071	0.158	0.405	2.42

Linear assumption underpredicts for large roll spacing

Empirical Bulging Equations

Bulging, δ (mm)

Roll pitch, L (mm)

Pressure, P (MPa)

Shell thickness, D (mm)

Shell temperature, T_{surf} (^oC)

Empirical bulging equations

NSC formula:

$$\delta = 1.893\times10^{-3}\, L^{3.3}\times P^{1.22}\times D^{-2.85}\times \exp(-5755/(T_{surf}+273))$$

Palmaers eq.:

$$\delta_{\max}(mm) = 0.4623\, C(T_{surf})\frac{P^{1.5}_{(kg/mm^2)}L^{5.12}_{(mm)}}{Vc^{0.22}_{(m/\min)}D^{3.8}_{(mm)}}$$

$$C(T_{surf}) = \begin{cases} 0.609\times10^{-4} & T_{surf}=900\,^\circ C \\ 0.725\times10^{-4} & T_{surf}=1000\,^\circ C \\ 0.929\times10^{-4} & T_{surf}=1100\,^\circ C \end{cases}$$

Lamant eq.:

$$\delta_{\max}(\mathrm{mm}) = 7.4088\times10^{-14}\exp(0.003866(\mathrm{T}_{\mathrm{surf}\,(^{o}\mathrm{C})}+273))\frac{\mathrm{L}^{7.16}_{(\mathrm{mm})}\mathrm{H}^{2.18}_{(\mathrm{m})}}{\mathrm{D}^{5.47}_{(\mathrm{mm})}\mathrm{Vc}^{0.4}_{(\mathrm{m/min})}}$$

Empirical bulging equations

Nippon Steel

$$\delta_{\max}(mm) = 1.893\times10^{-3}\exp\left(\frac{-5755}{T_{surf\,(^\circ C)}+273}\right)\frac{P^{1.22}_{(kg/cm^2)}L^{3.3}_{(mm)}}{D^{2.85}_{(mm)}}$$

Lan Yu eq.

$$\delta_{\max}(mm) = 7.1496\times10^{-34}F\,\frac{P^{1.993}_{(MPa)}L^{6.5}_{(mm)}T^{8.766}_{surf\,(^\circ C)}}{D^{5.333}_{(mm)}}$$

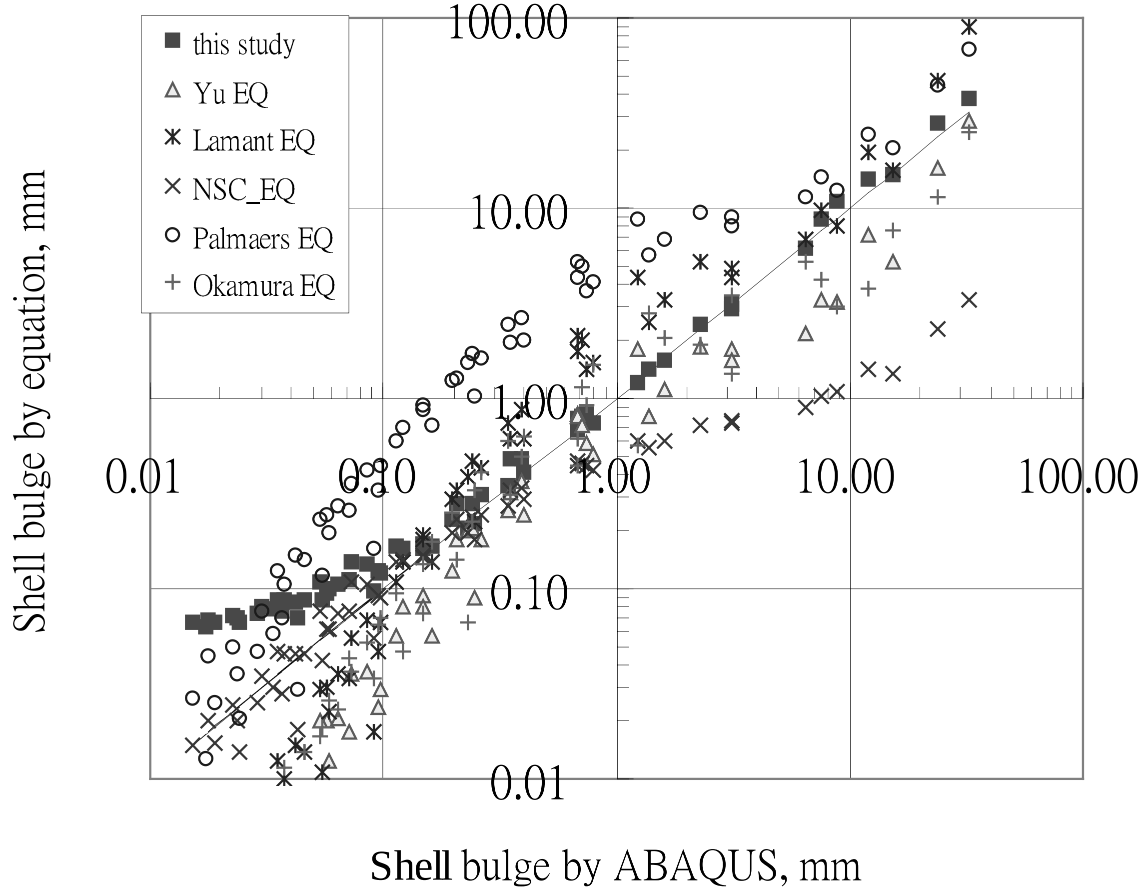
where: $F = 1-\left(\frac{\pi W}{2L}\tanh\left(\frac{\pi W}{2L}\right)+2\right)\Big/2\cosh\left(\frac{\pi W}{2L}\right)$

New Equation (this study)

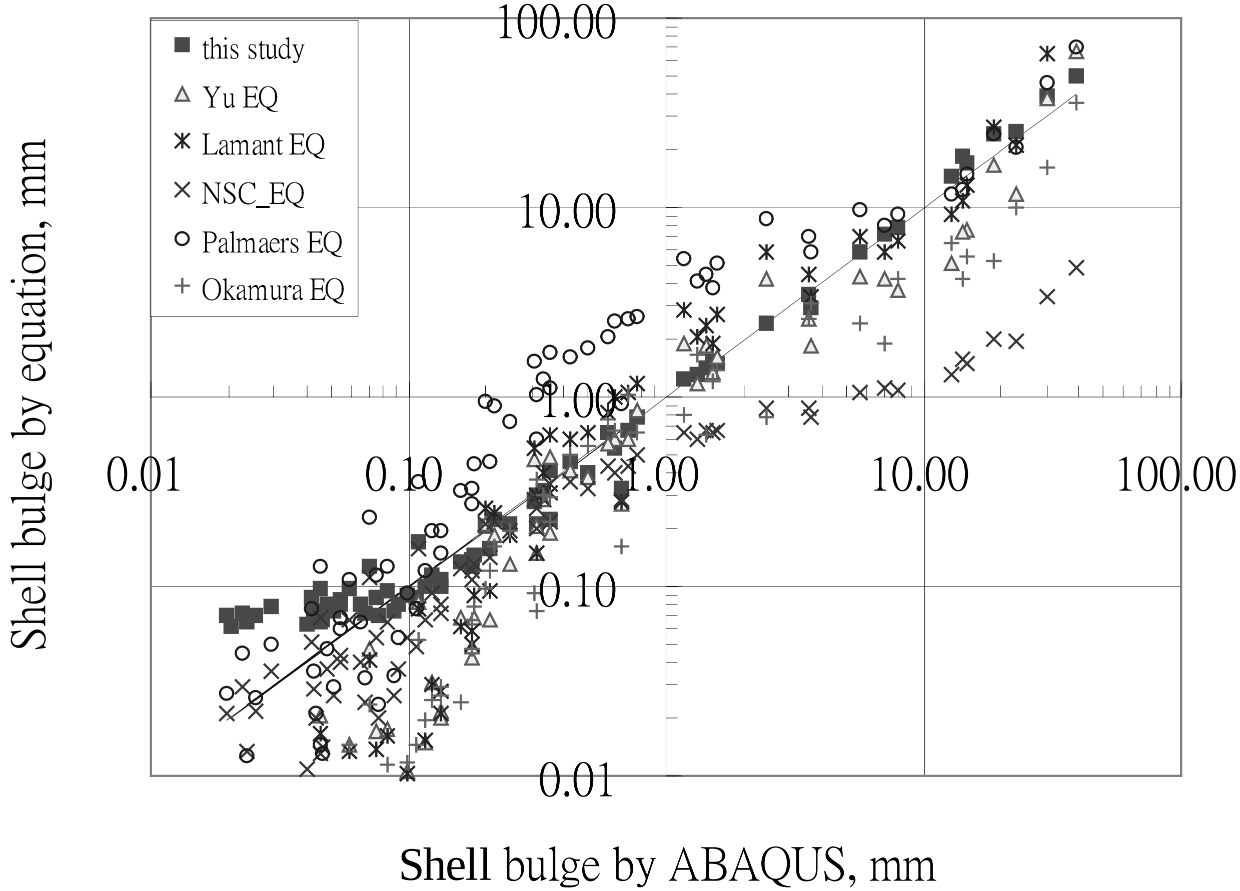
$\delta = 0.055*\exp[(1.94*10^{-5}*T_{surf} - 0.0085) * (L^{2.52}*P*D^{-2.2})]$

IF δ >10mm, $\delta = (0.0137* T_{surf}+23.6)*\ln(L^{2.52} *P *D^{-2.2}) -220$

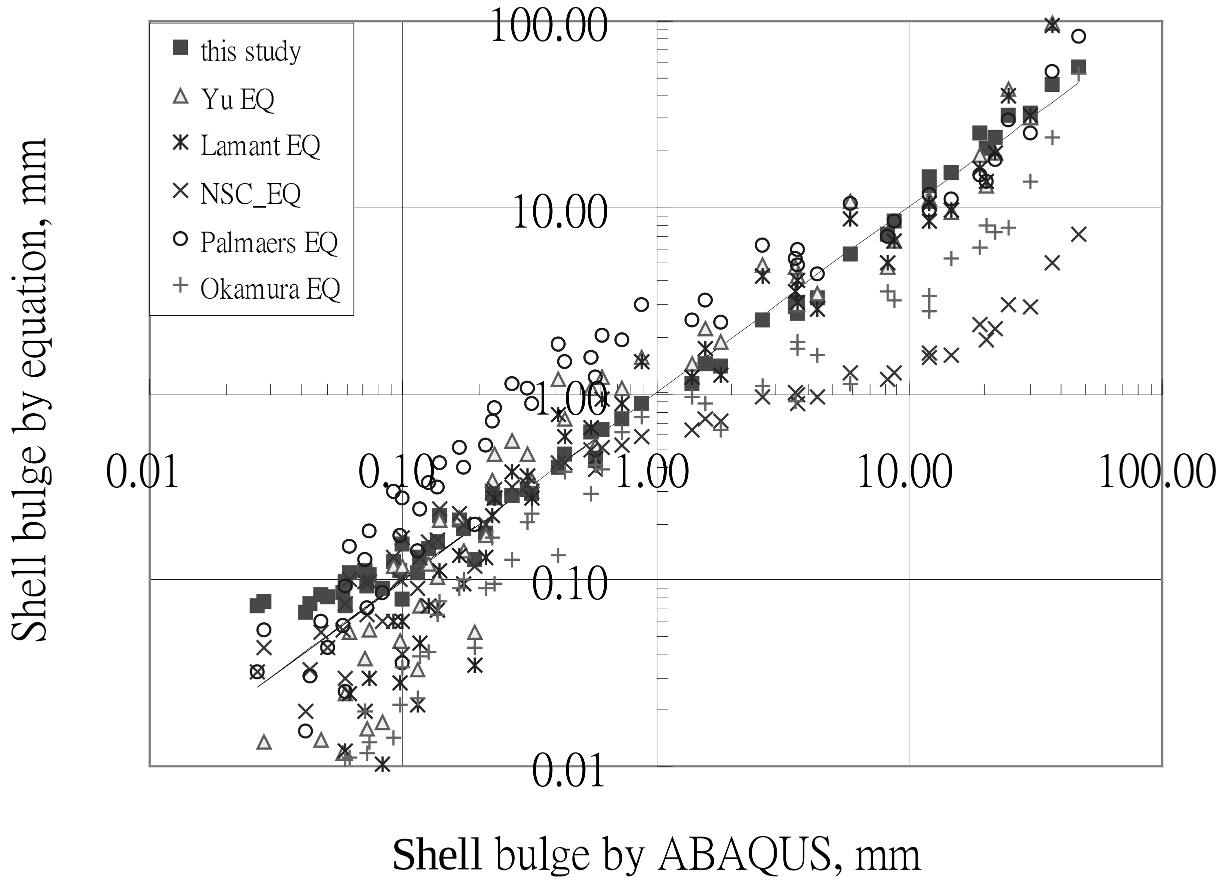
Comparison of bulging eqs predictions T_{surf} = 800 °C



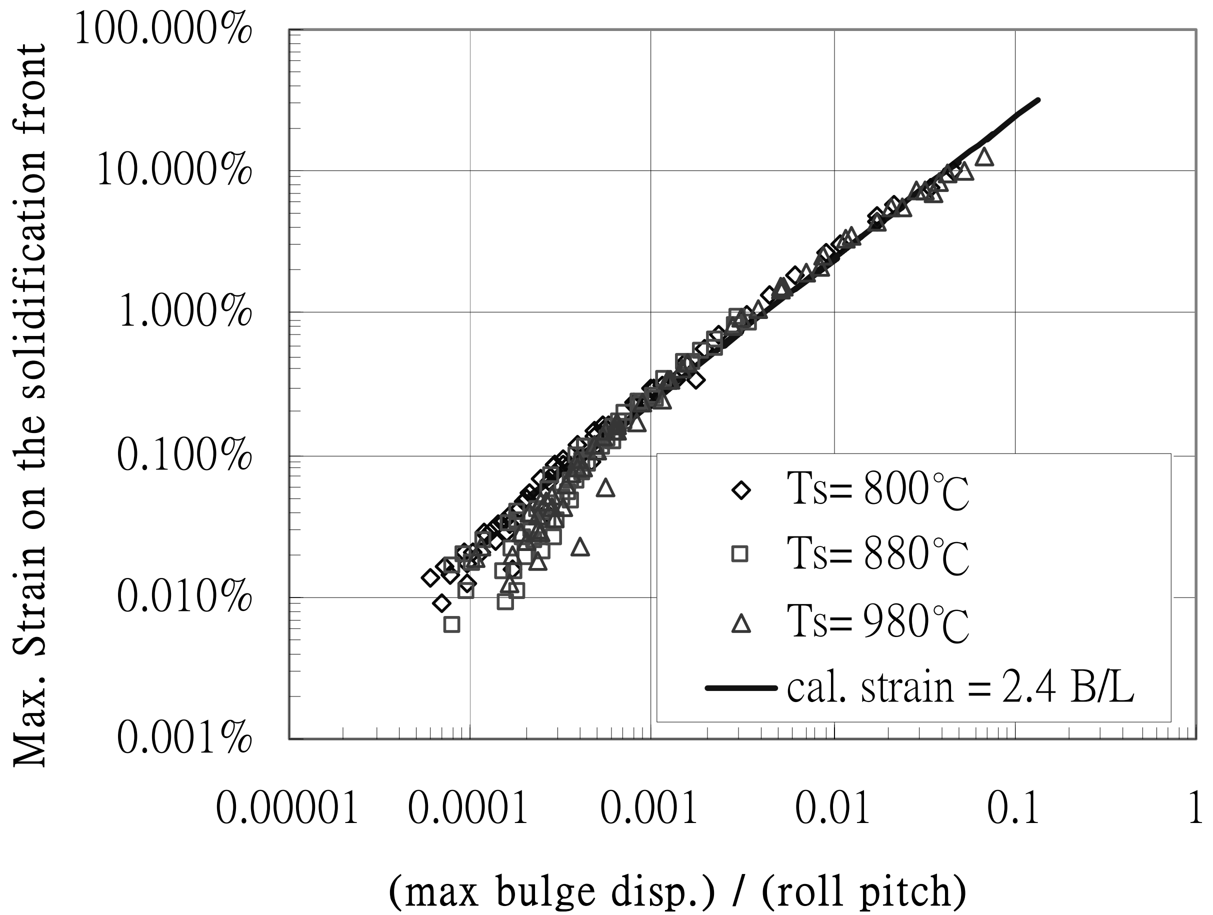
Comparison of bulging eqs predictions T_{surf} = 880 °C



Comparison of bulging eqs predictions T_{surf} = 980 ^oC



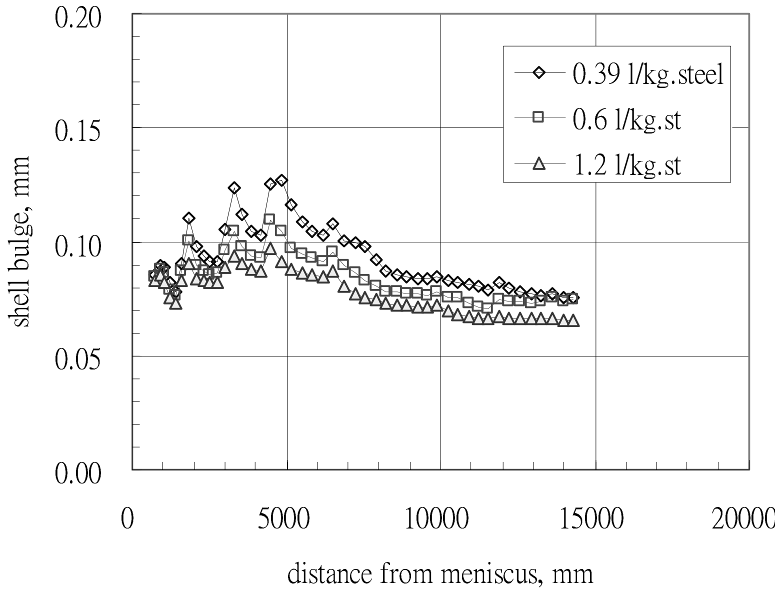
Strain on solidification front depends on bulging and roll pitch

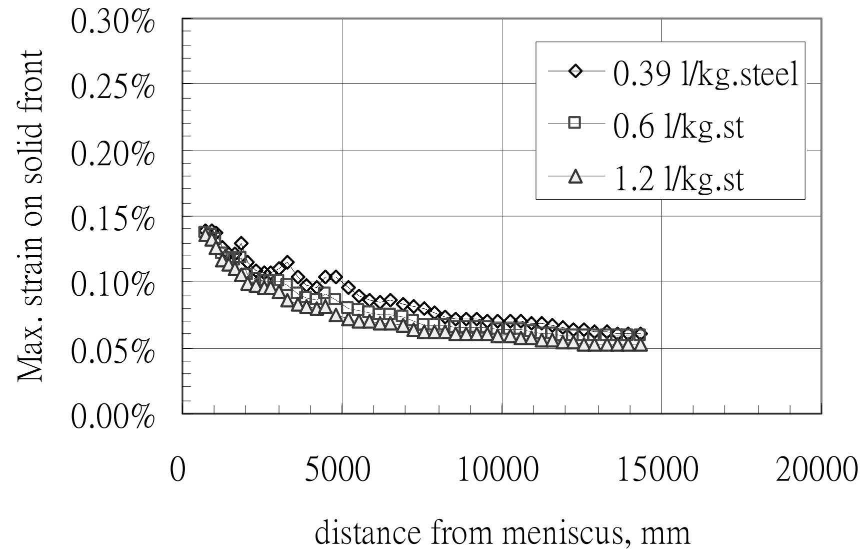


Calculated bulging and strain between support rolls

(#1SCC Caster; 0.39 l/kg.steel cooling)

perfect alignment

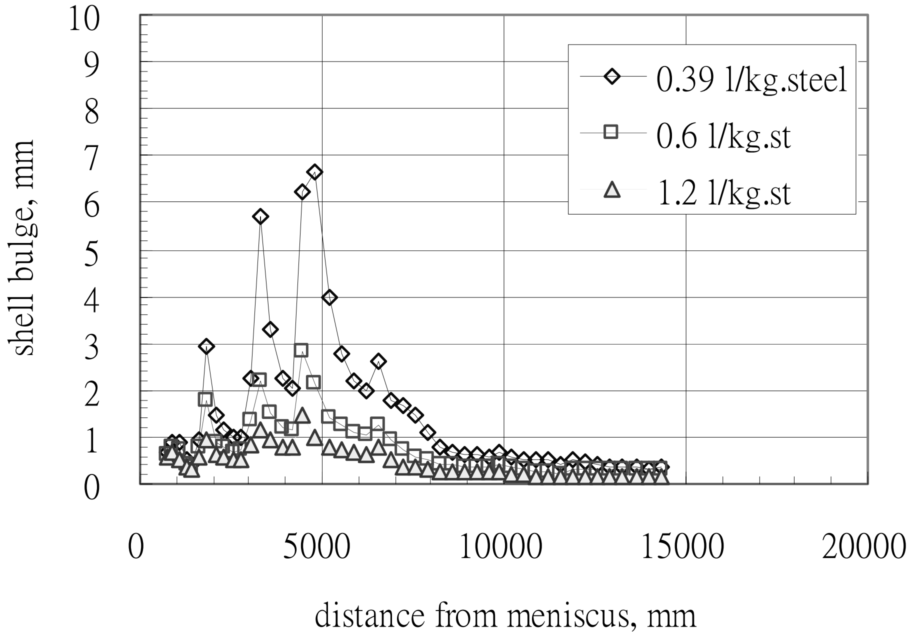


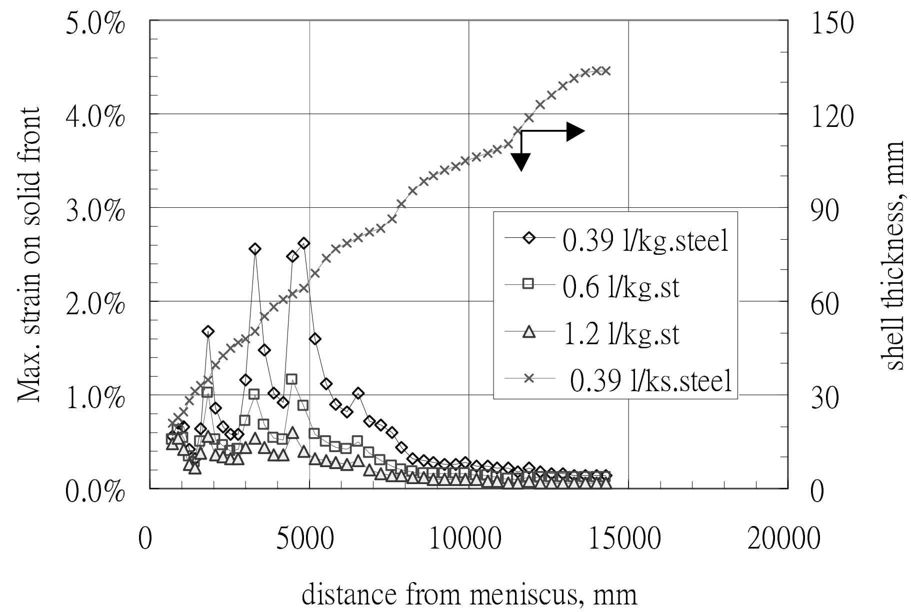


Calculated bulging and strain between support rolls

(#1SCC Caster; 0.39 l/kg.steel cooling)

One roll missing





Conclusions

- Roll contact length from FEM contact analysis is quantified with a simple equation and subtends an angle of about 1.6 degrees
- Bulging from FEM analysis is quantified with a simple empirical equations
- Solidification front strain is directly related to max. bulging and roll pitch
- Internal cracks due to strain at solidification front are unlikely with perfect roll alignment.
- Increasing cooling intensity may lower strain below critical, if misalignment is severe
- Reducing misalignment should be more effective at avoiding internal cracks and segregation than increasing spray zone cooling