CCC Annual Report

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# *Modeling and On-Line Measurements of Narrow Face Mold Taper*

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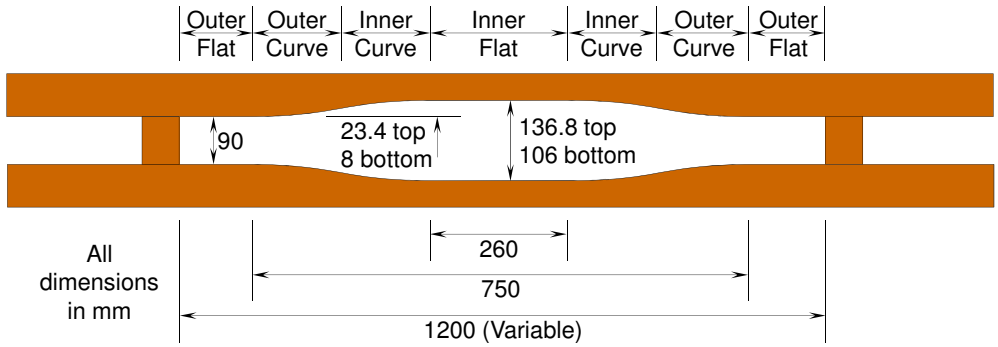
## Introduction

- Narrow face mold taper has been measured online with inclinometers at Tata Steel IJmuiden
  - Funnel-mold thin slab caster
- Modeling of thermomechanical behavior of mold has been able to match steady-state measurements of taper
- This work focuses on the behavior of the narrow face mold during startup

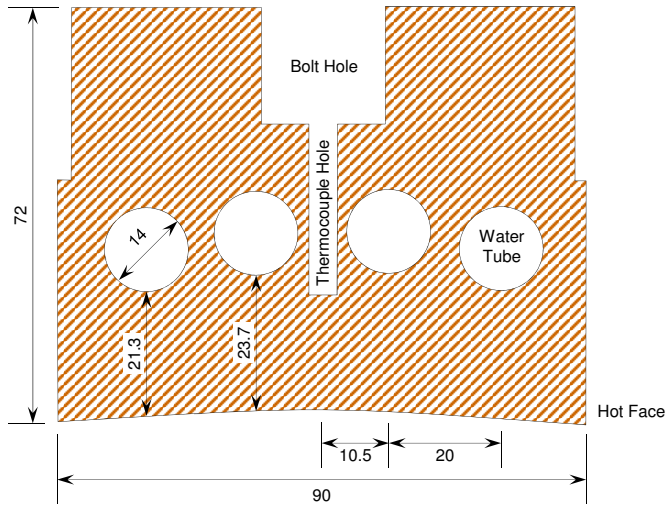
# Funnel Mold Geometry



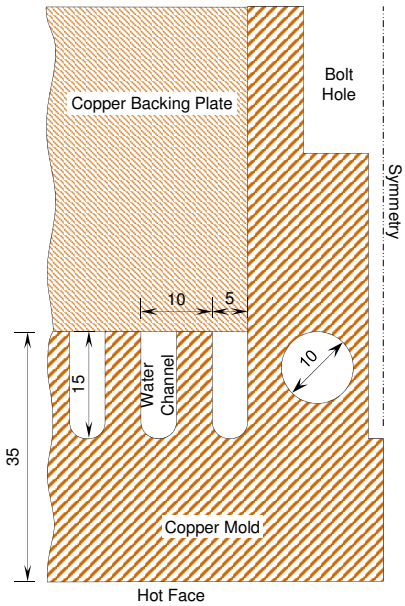

- Cu-Cr-Zr alloy
  - 350 W/(m·K) thermal conductivity
  - 8900 kg/m³ mass density
  - 385 J/(kg·K) specific heat capacity
  - 117 GPa Young's modulus, 0.181 Poisson's ratio
- No coating layers



# Water Channel Geometry



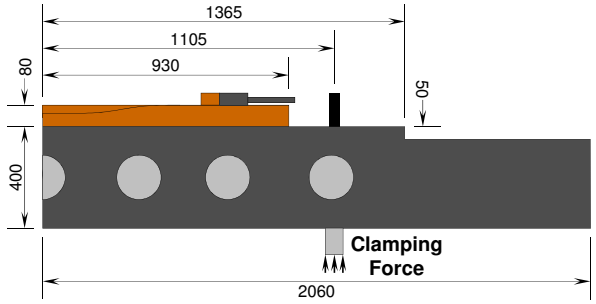

Narrow face



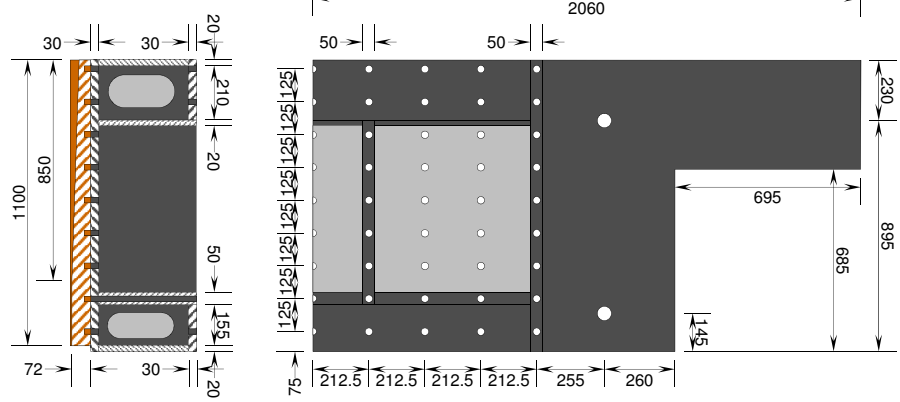

Wide face

# Waterbox Geometry

- 316 stainless
  - 200 GPa Young's modulus
  - 0.3 Poisson's ratio




All dimensions in mm

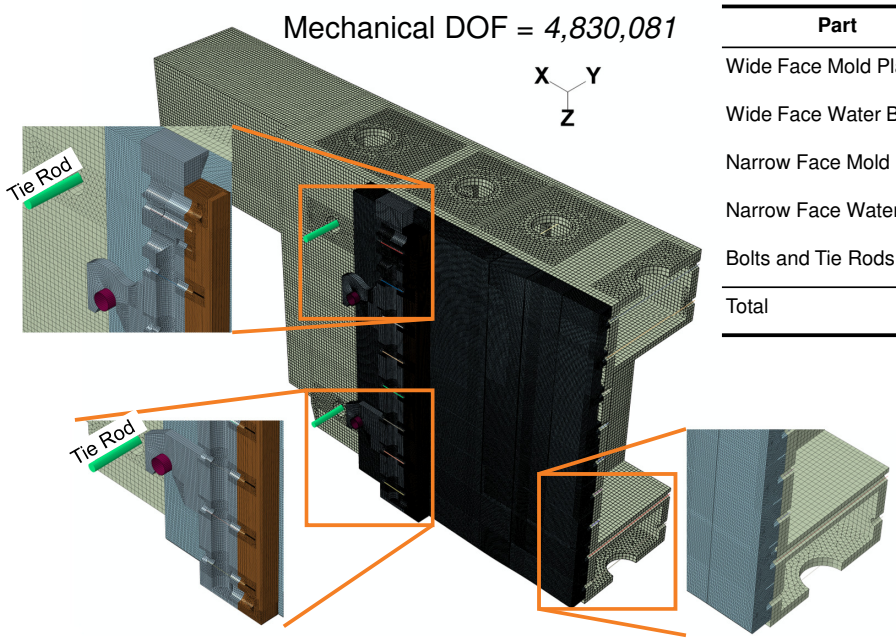





# Finite-Element Mesh

Thermal DOF = *1,089,166*

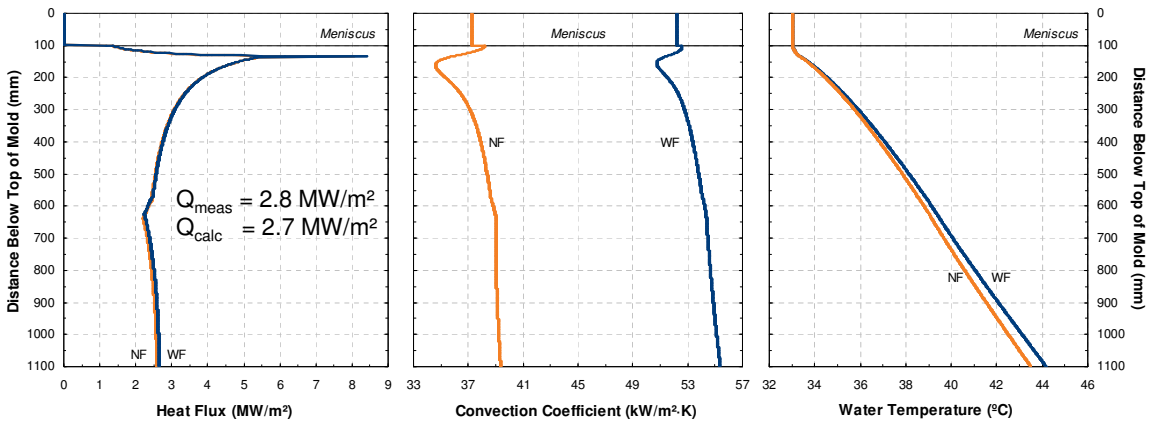
Mechanical DOF = *4,830,081*




| Part | Nodes | Elements |
|---|---|---|
| Wide Face Mold Plate | 855,235 | 4,223,072 |
| Wide Face Water Box | 185,534 | 190,457 |
| Narrow Face Mold Plate | 233,931 | 495,566 |
| Narrow Face Water Box | 83,269 | 239,604 |
| Bolts and Tie Rods | 110 | 55 |
| Total | 1,358,081 | 5,148,754 |

# Thermal Boundary Conditions

- Specified heat flux on mold hot faces $-k\,\nabla T \cdot \boldsymbol{n} = \boldsymbol{q}^{sp} \cdot \boldsymbol{n}$
- Convection BC on water channels $-k\,\nabla T \cdot \boldsymbol{n} = h\left(T - T_{\infty}\right)$
- All other faces thermally insulated $-k\,\nabla T \cdot \boldsymbol{n} = 0$
- Values calculated from CON1D calibrated to plant measurements [Santillana *et al.*, ISIJ Int. 2008]



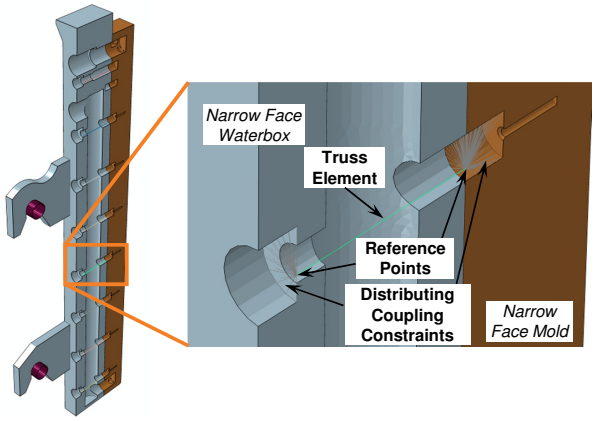



# Mechanical Boundary Conditions

- Ferrostatic pressure on hot faces
- Symmetry on appropriate planes
  - Wide face mold and waterbox centerline
  - Narrow face mold and waterbox centerline
  - Tie rod centerlines
- Mechanical contact on mating faces
  - "Hard" contact algorithm within ABAQUS
  - Copper-copper coefficient of static friction $\mu$ = 1.0 [-]
  - Copper-steel coefficient of static friction $\mu$ = 0.5 [-]

# Mold Bolts and Tie Rods

| Bolt | Length (mm) | Cross-Sectional Area (mm²) | Applied Torque (N·m) | Pre-Load (kN) | Pre-Stress (MPa) | Stiffness (MN/m) |
|---|---|---|---|---|---|---|
| NF (Short) | 150 | 181 | 100 | 30 | 168 | 240 |
| WF Short | 87 | 187 | 100 | 30 | 162 | 424 |
| WF Long | 449 | 143 | 100 | 30 | 212 | 63 |
| Upper Tie Rod | 1335 | 1215 | -- | 40 | 33 | 34.8 |
| Lower Tie Rod | 1335 | 1215 | -- | 70 | 58 | 33.4 |

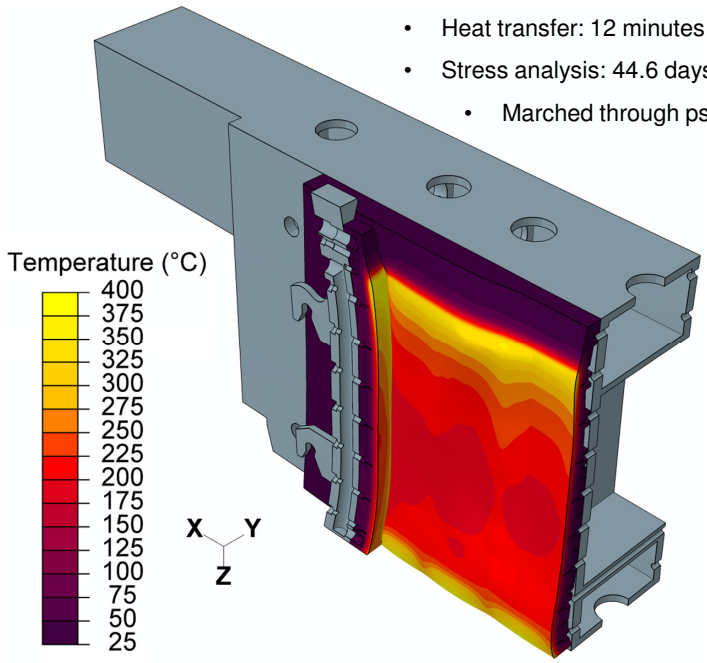



- Bolts modeled as truss elements and prestressed according to plant practice
  - See [Thomas *et al.*, Iron and Steelmaker 1998]
- "Distributing coupling constraints" tie bolt ends to surfaces on mold pieces
- Simulated tie rods account for actual tie rods and spring packs



# Steady-State Simulation Results

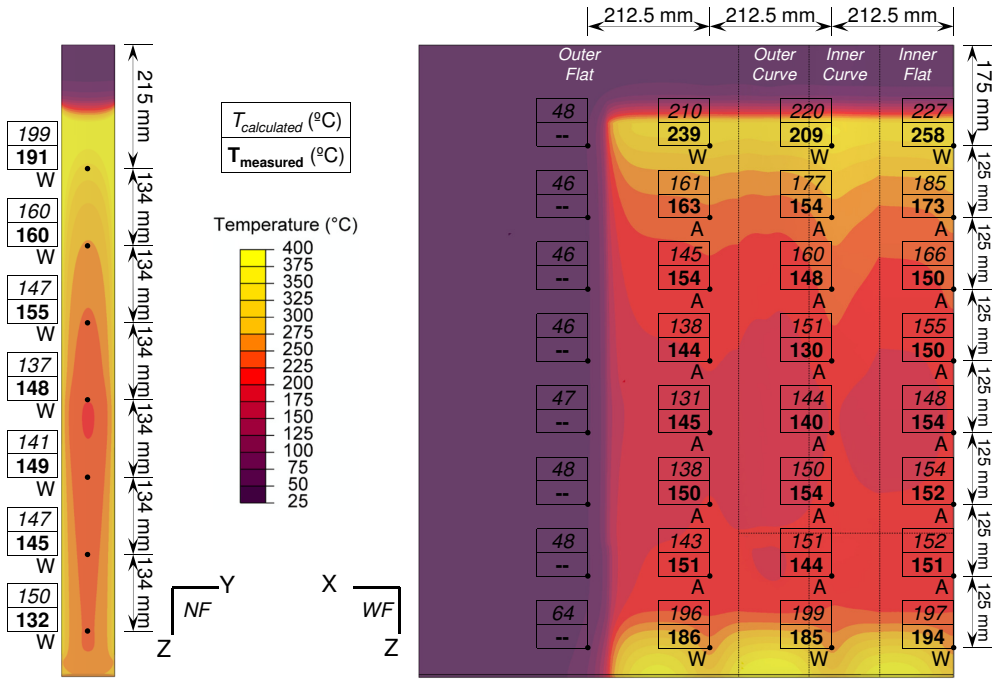
- Heat transfer: 12 minutes on 8-core 2.66 GHz Intel Xeon
- Stress analysis: 44.6 days on 8-core 2.66 GHz Intel Xeon
  - Marched through pseudo-time to get a solution




50× scaled distortion

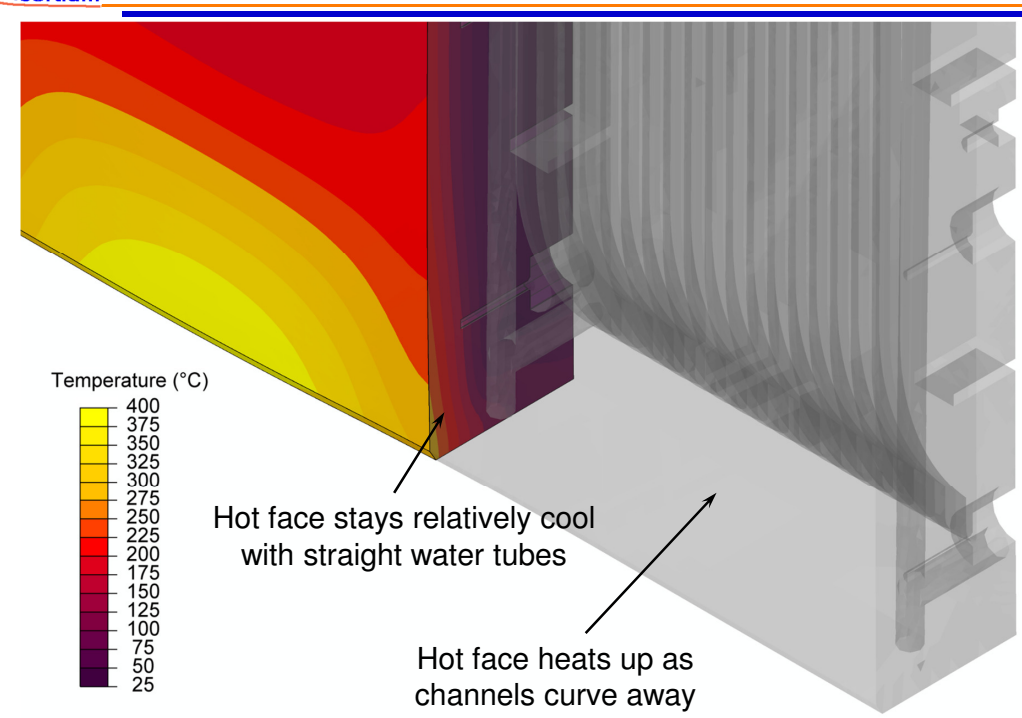
# Thermocouple Validation

## *Corrected for Wire Convection*



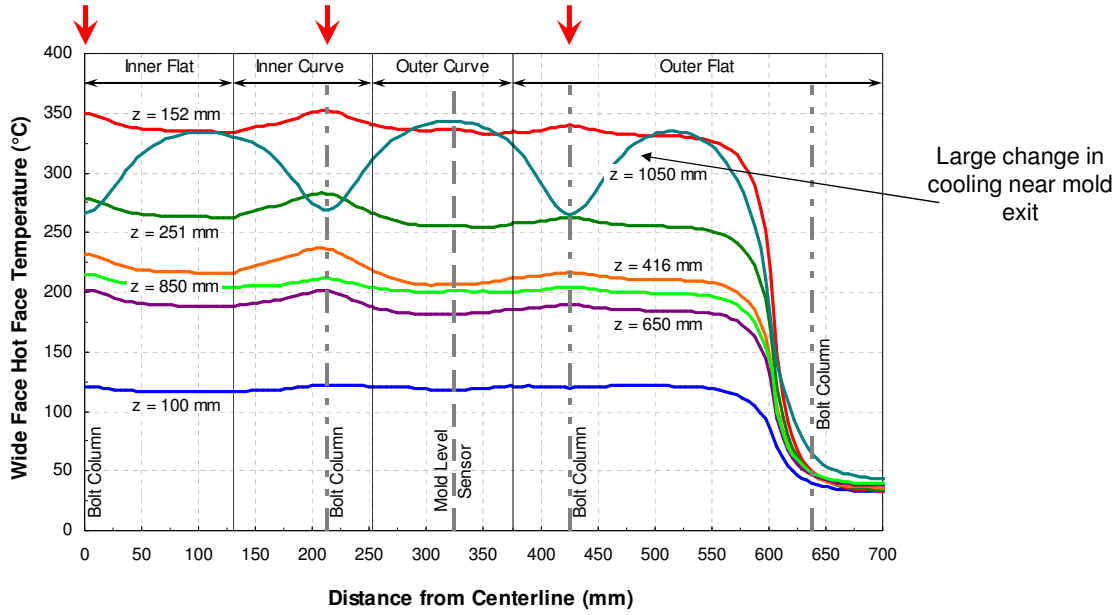



# Cooling Near Mold Exit



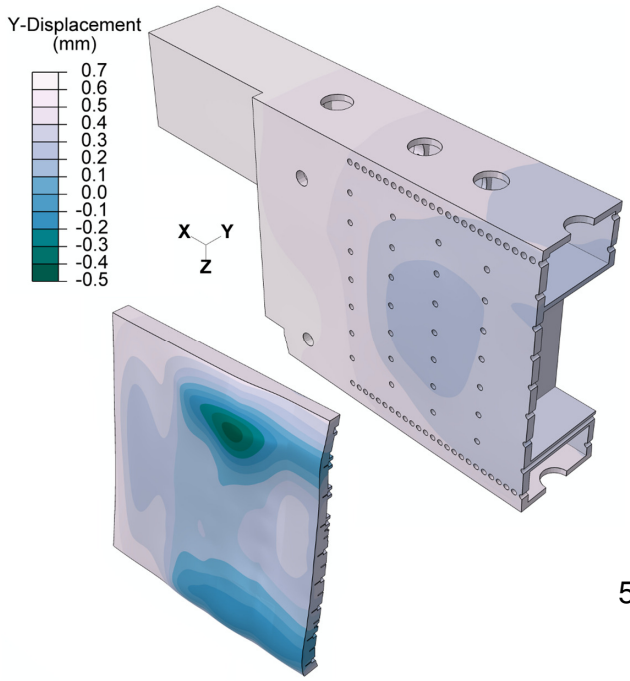
# Wide Face Temperatures

Slight 2D heat transfer in funnel region (less than 2 ºC), but change in cooling around bolts is more significant



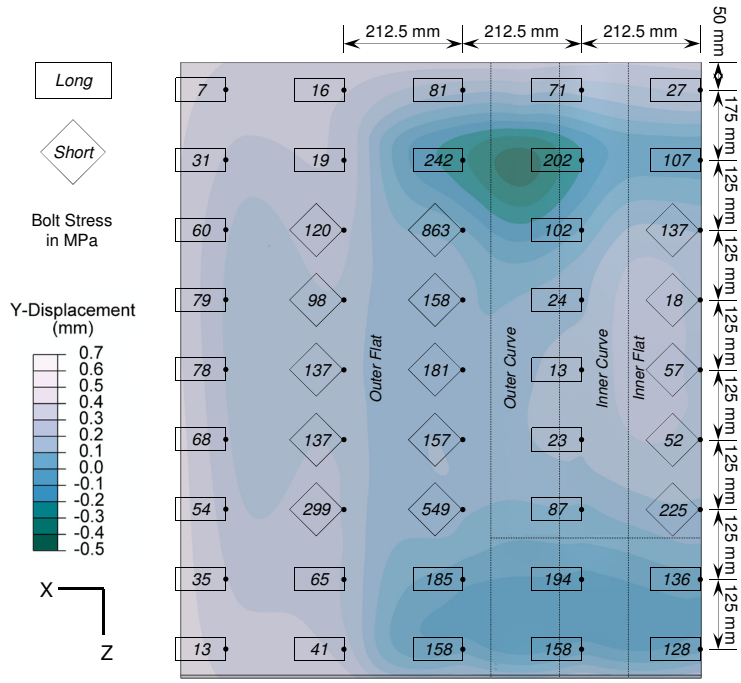



# Wide Face Mold Distortion



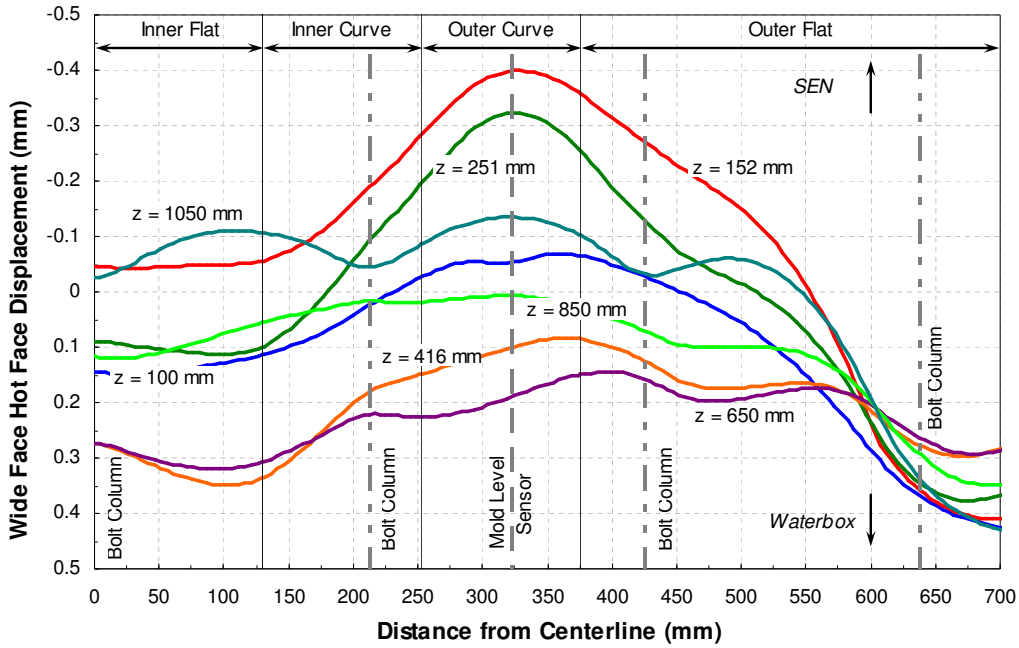

50× scaled distortion

# *Wide Face Mold Distortion*
# Out-of-Plane Behavior



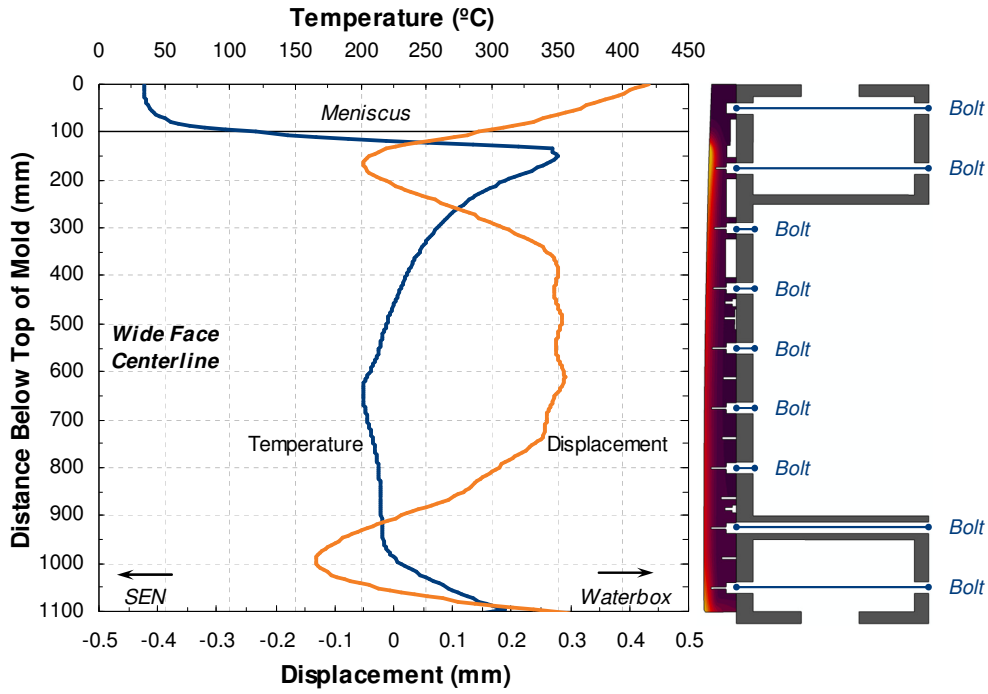



# *Wide Face Mold Distortion*
# Out-of-Plane Behavior



## *Wide Face Mold Distortion*

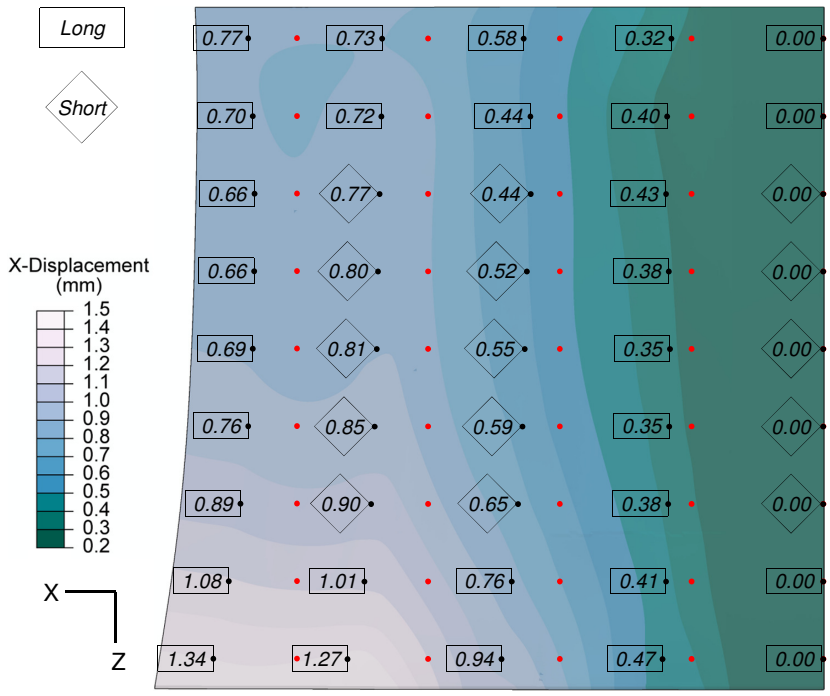
# Behavior at Centerline






## *Wide Face Mold Distortion*

# In-Plane Behavior – Towards NF



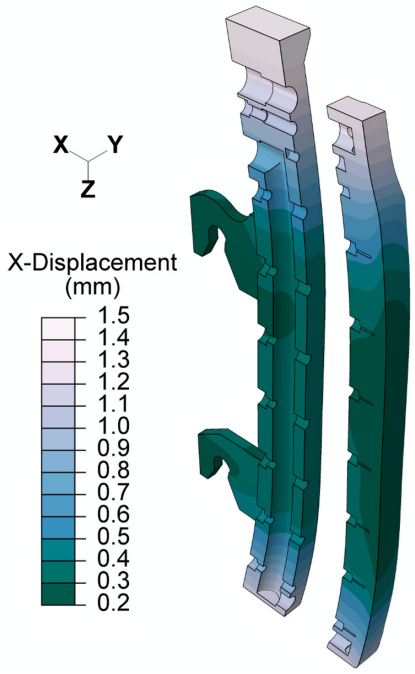

100× scaled distortion in x-direction

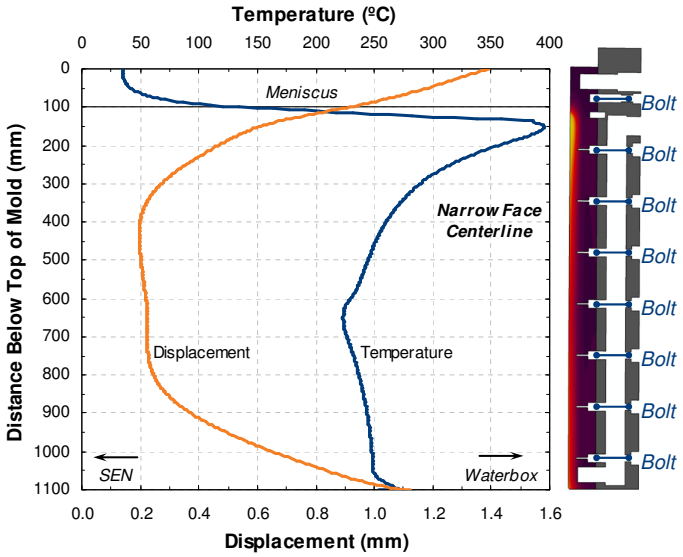
# Wide Face Mold Distortion

- Distorts into a 'W' vertically and horizontally
  - Largely because of different stiffnesses of bolts
- Distortion follows bolting pattern more than the thermal response
  - Short bolts provide most resistance to distortion
- Cold edges constrain against distortion
- Most severe distortion
  - Just below meniscus and just above mold exit
  - In between bolt columns



# Narrow Face Mold Distortion



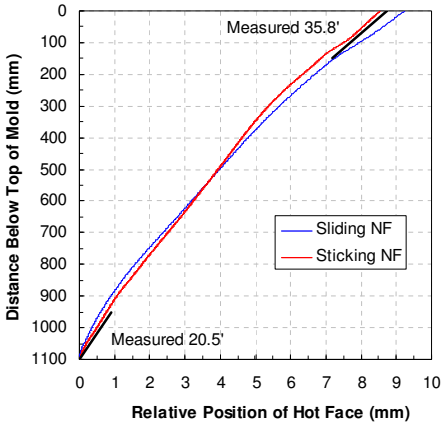
# NF Taper Measurements

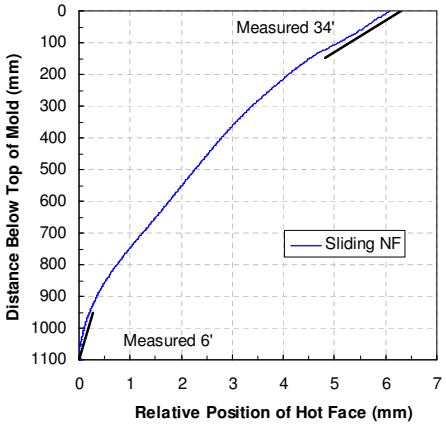
Measurements during startup

| | Measured | Calculated, sliding NF | Calculated, sticking NF |
|---|---|---|---|
| Top | 35.8’ | 39.6’ | 33.7’ |
| Bottom | 20.5’ | 14.6’ | 19.6’ |

Measurements during steady casting

| | Measured | Calculated, sliding NF |
|---|---|---|
| Top | 34’ | 33.2’ |
| Bottom | 6’ | 6.1’ |



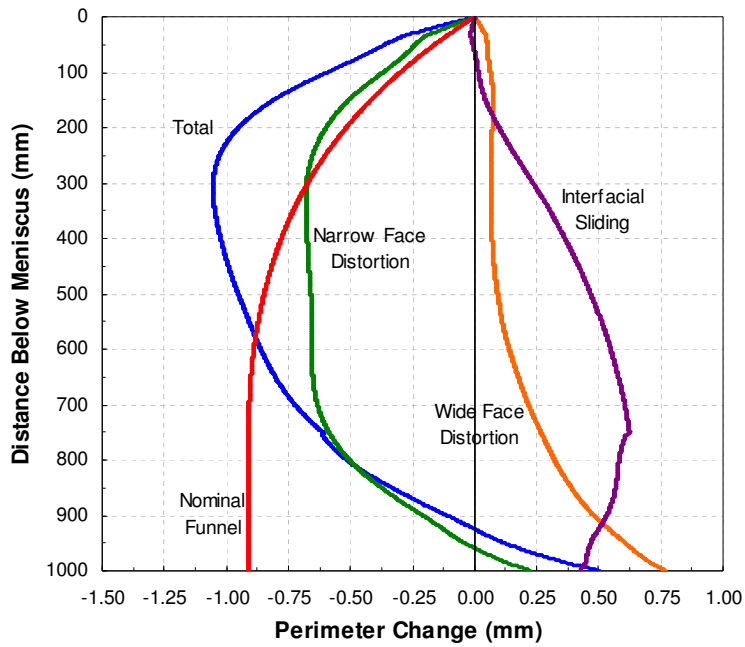



# Narrow Face Mold Distortion

- Narrow face distorts into roughly-parabolic arc
  - Typical behavior
  - Elongates by 2 mm
- Low bolt operating stresses
  - No risk of bolt tensile failure
- Small bolt displacement at mold/waterbox interface
  - 16 mm bolts in 22 mm holes
  - No risk of mold overconstraint or bolt shearing failure
- Waterbox hooks provide extra rigidity to assembly
  - Causes wobble in distortion profile
  - Bolts near hooks do not overcome prestress

# Effect of Distortion on NF Taper

- Calculate perimeter of mold as function of distance down the mold
- Contributions from
  - Funnel geometry
  - Wide face expansion
  - Narrow face distortion
  - Prevented sliding of WF relative to rigid NF
- Sliding should be considered during startup and in molds with rigidly positioned NFs





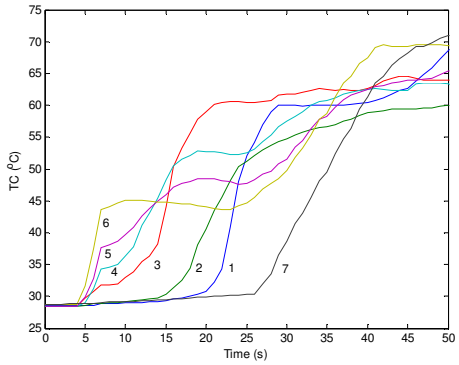

# Conclusions

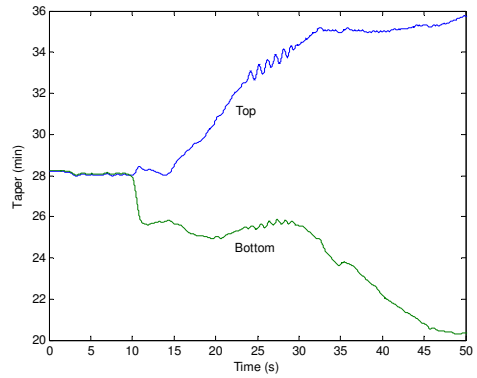
## *Mold/Waterbox Behavior*

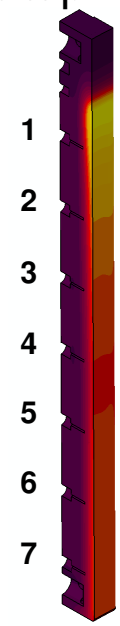
- WF distortion complicated because of bolts
- NF distortion typical
- Good design principle: oversize bolt holes in the waterbox to allow transverse movement
- Distortion has a significant effect on taper
  - Not linear with distance down the mold
  - Room-temperature calculations are insufficient
- More details found in
  - Hibbeler *et al.*, *Met. Trans. B*, **43** (2012) p. 1156.

# Startup Transient

- Inclinometer and thermocouple data from a startup provides great validation for exploring mold behavior during a startup
- TC temperature show first-order behavior
  - Time constant about 5 seconds



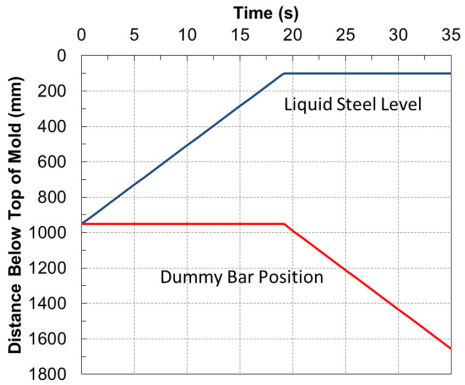


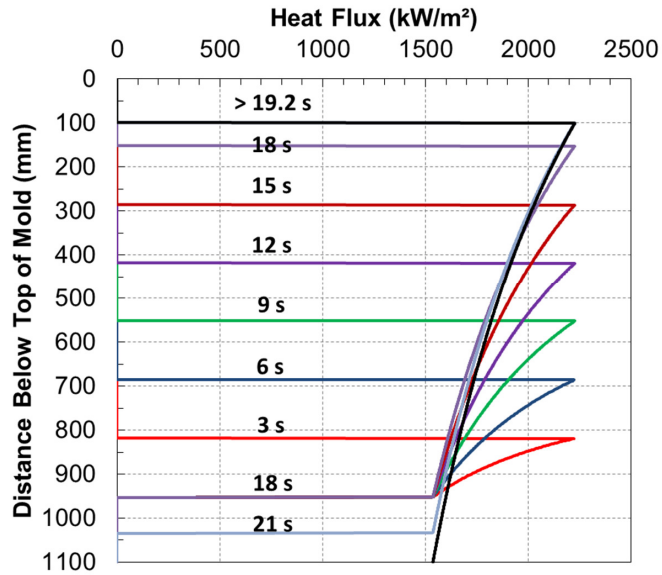

# Startup Heat Flux Profile

- Assume that the heat flux profile has a certain shape, $q(z) = \frac{q_0}{\sqrt{1+z}}$, applied over a region from $z = z_{top}$ to $z = z_{bot}$.
- Stretch this profile by changing $z_{top}$ according to filling a rectangular prism and $z_{bot}$ according to dummy bar movement
- Estimate filling rate: $Q = 0.0048\ m^3/s$
- Filling time $t_{fill} = w_{slab} t_{mold} (z_{start} - z_{menisucs})/Q$ gives

$$z_{top} = \begin{matrix} z_{start} - Vt & if\ t < t_{fill} \\ z_{menisucs} & if\ t > t_{fill} \end{matrix} \qquad z_{bot} = \begin{matrix} z_{start} & if\ t < t_{fill} \\ z_{start} + V(t - t_{fill}) & if\ t > t_{fill} \end{matrix}$$

# Startup Heat Flux Profile

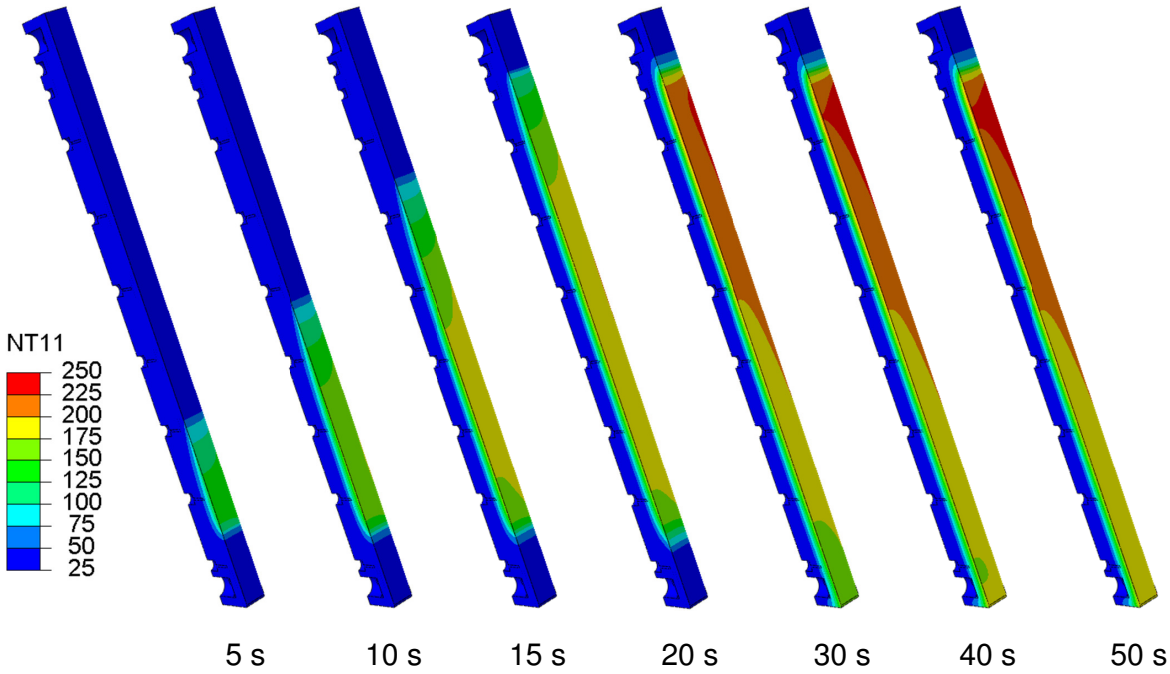


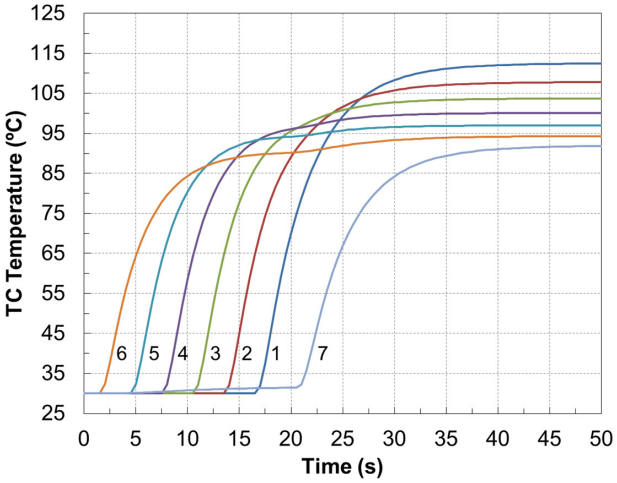

A *rough* first approximation to the startup heat flux

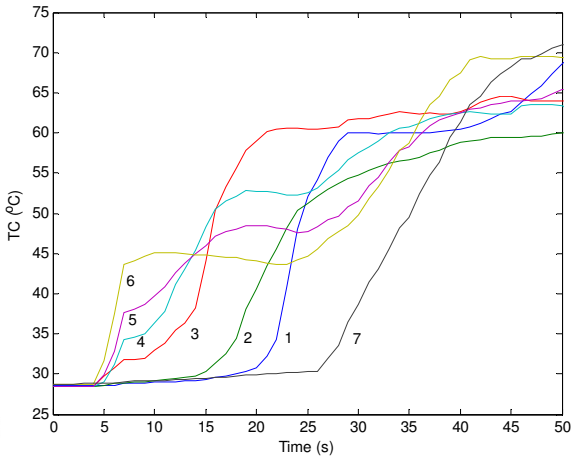


# Startup Thermal Behavior



# Thermocouple History




- Obviously, heat load BC needs improvement
- Two-stage filling of mold
  - "Waterfall" until mold level covers nozzle ports
  - "Pipe flow" after ports are submerged



# Conclusions

## *Mold Startup Behavior*

- Preliminary study of mold startup provides reasonable results
  - Mechanical simulations to come: try to match taper measurements
- Heat flux boundary condition needs improvement
  - Use plant data (stopper rod position, nozzle geometry, dummy bar/casting speed history, etc.)
- Inclinometers are a good tool to use for measuring taper during casting

# Acknowledgments


- Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Magnesita Refractories, Nippon Steel and Sumitomo Metal Corp., Nucor Steel, Postech/ Posco, Severstal, SSAB, Tata Steel, ANSYS/ Fluent)
- National Center for Supercomputing Applications (NCSA) at UIUC
- Ronald Schimmel, Gert Abbel, Henk Visser, Dirk van der Plas, and others at Tata Steel IJmuiden