# Adapting Smart Dynamic Casting to Thin Folded Geometries

**Other Conference Item**

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National Centre of Competence
in Research
Digital Fabrication

# Adapting Smart Dynamic Casting to Thin Folded Geometries

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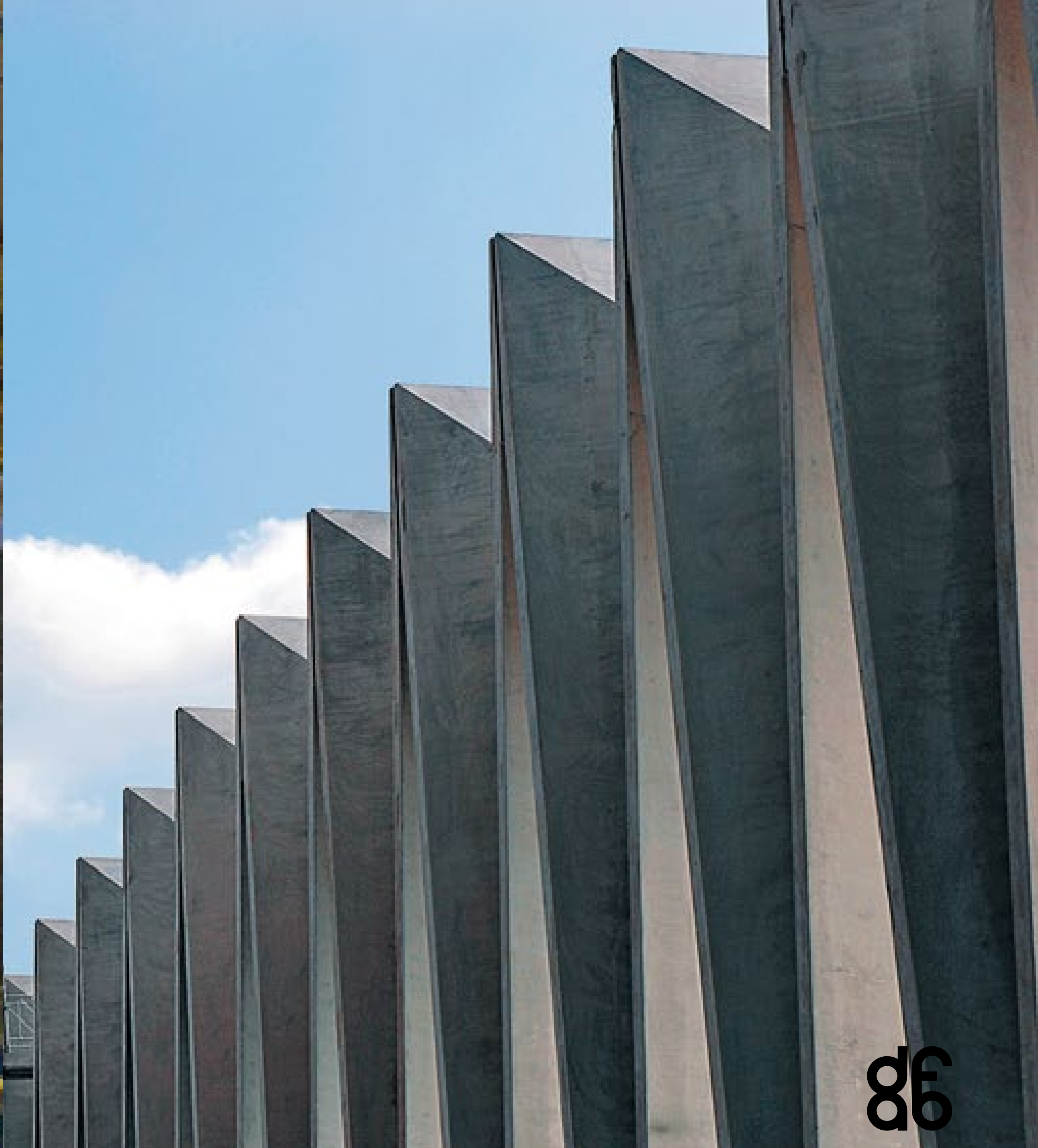
NCCR Digital Fabrication
Collaboration between Gramazio Kohler Research and the group of Physical Chemistry of Building Materials

# Adapting Smart Dynamic Casting to Thin Folded Geometries

- Introduction
- Slipforming process model
- Material adjustments
- Conclusion and outlook

# Introduction



*Mühlimatt Sports Centre, Studio Vacchini Architetti, 2010*

# Smart Dynamic Casting

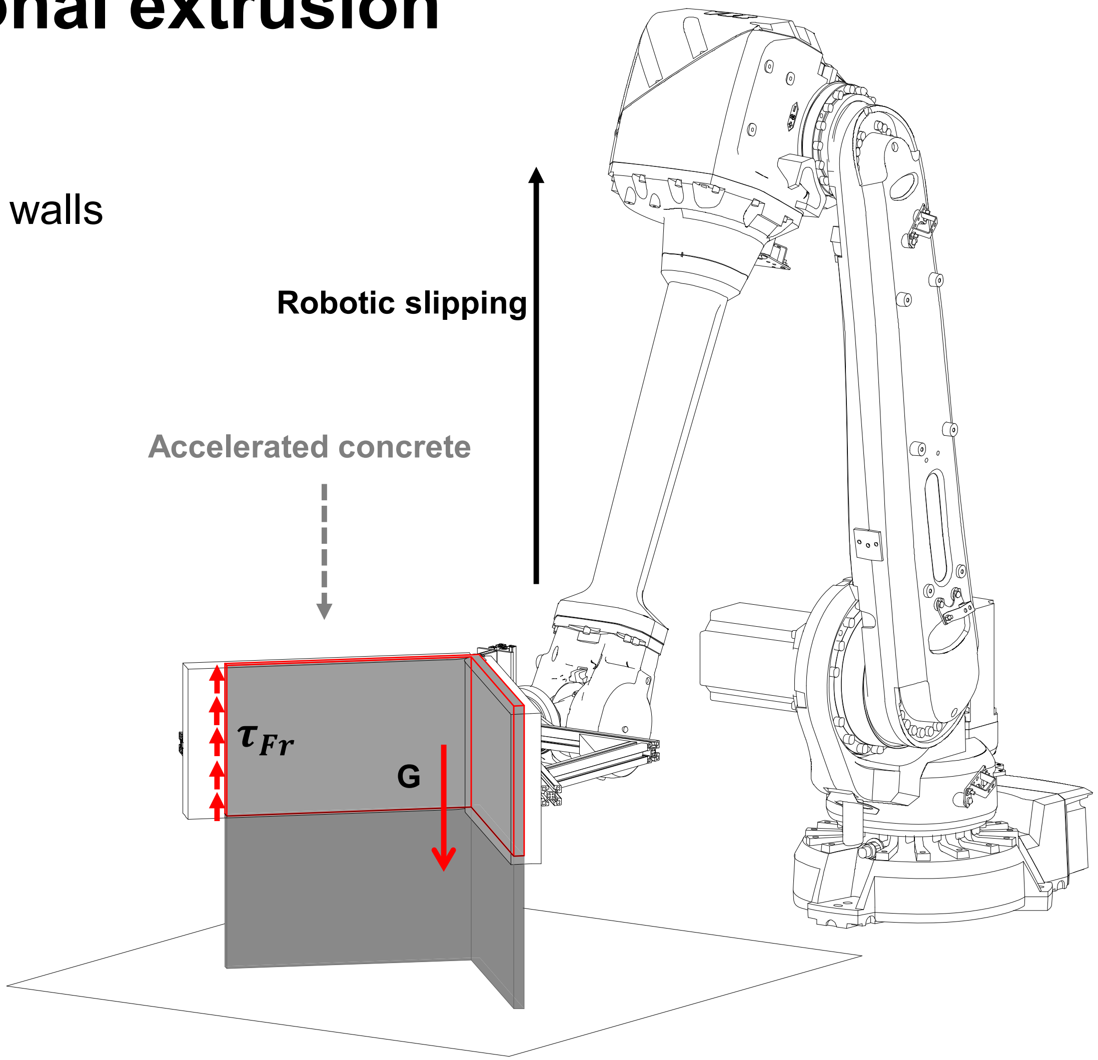
- Robotic slipforming prefabrication
- Formwork moved along a digital trajectory
- Shaping the concrete

***Smart Dynamic Casting production for the DFAB house, Gramazio Kohler Research, ETH Zürich***

# Smart Dynamic Casting

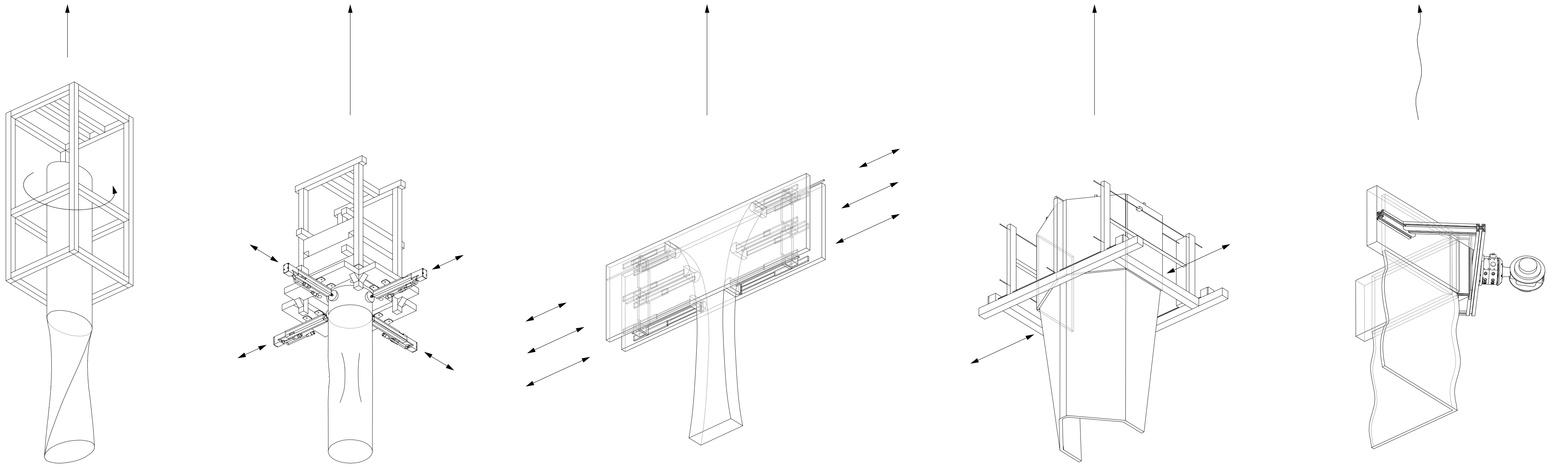
# Slipforming process model – gravitational extrusion

weight of concrete in the formwork <-> friction along the formwork walls



# Slipforming process model – formworks

weight of concrete in the formwork <-> friction along the formwork walls



SDC Columns

SDC Mullions

SDC Thin-walled


SDC Columns

SDC Mullions

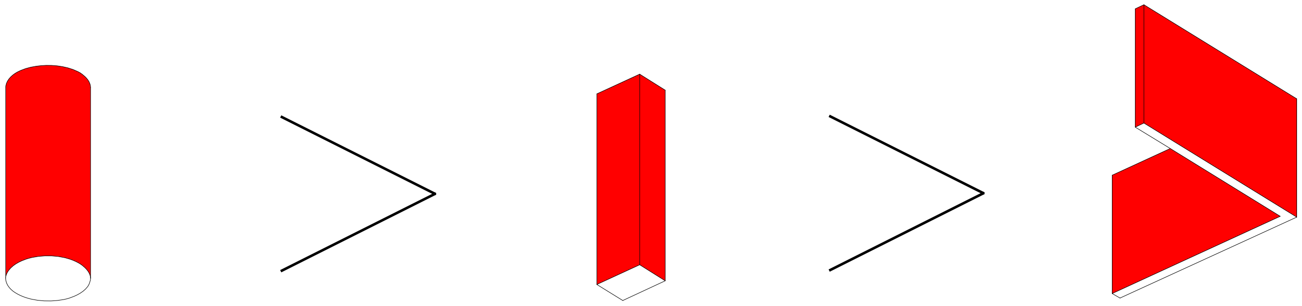

SDC Thin-walled

# Slipforming process model – formworks

Slipforming as gravitational extrusion: weight of concrete in the formwork <-> friction along the formwork walls

Differences in hydrodynamic radius

$$r_{hy} = \frac{2 \cdot Volume}{Surface}$$



$r_{hy,columns}$ = 75mm $r_{hy,mullions}$ = 41mm $r_{hy,folded}$ = 25mm

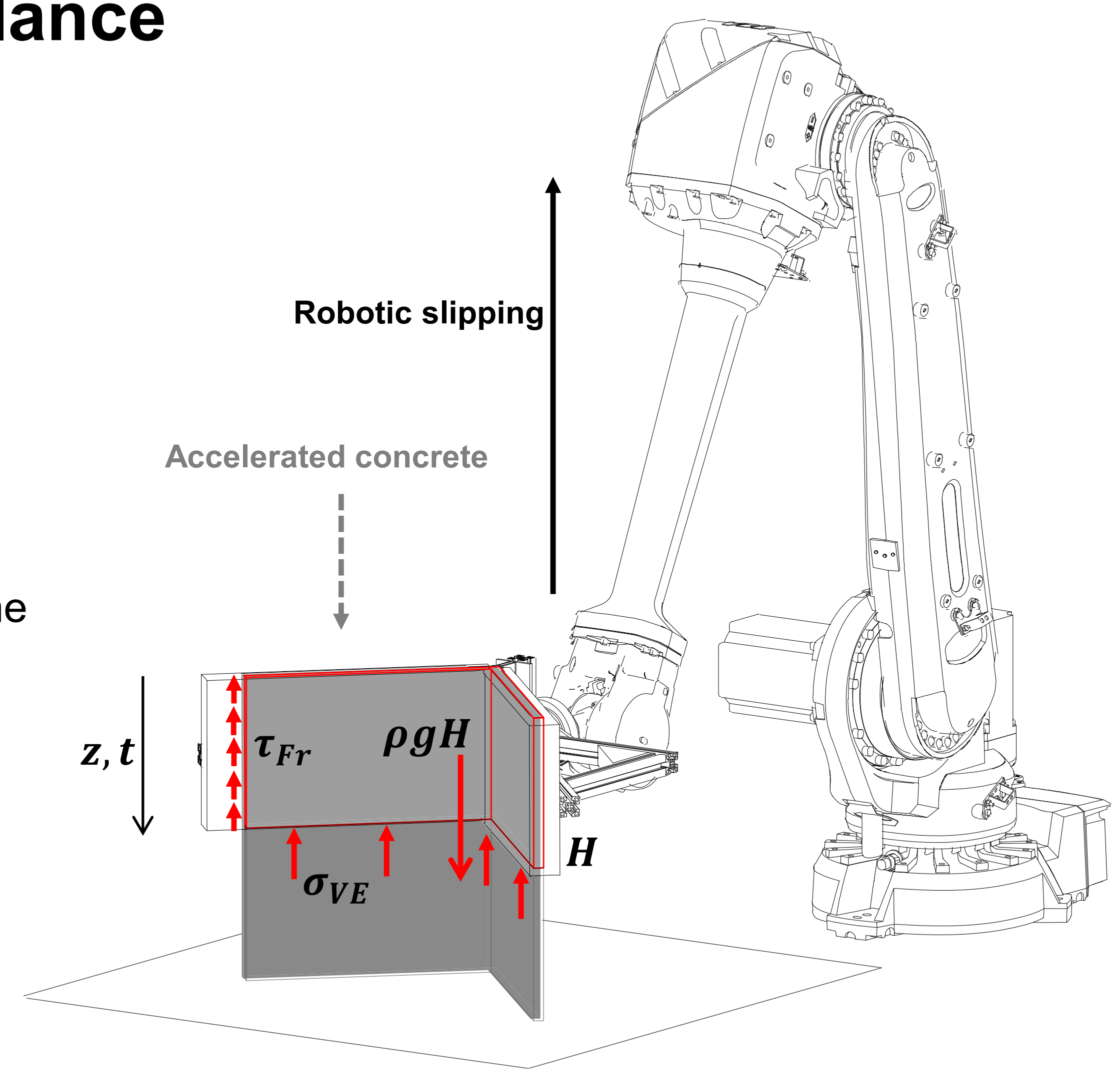
# Slipforming process model – force balance

Force balance in the formwork:

$$\sigma_{VE} = \rho g H - \frac{2}{r_{hy}} \int_0^z \tau_{Fr}(z)\, dz$$

- Friction $\tau_{Fr}(t)$ is proportional to the yield stress
- Yield stress evolves according to a power law scaling over time

$$\tau_{Fr}(t) = \boxed{\alpha_{Fr}}\, \tau_0(t)$$



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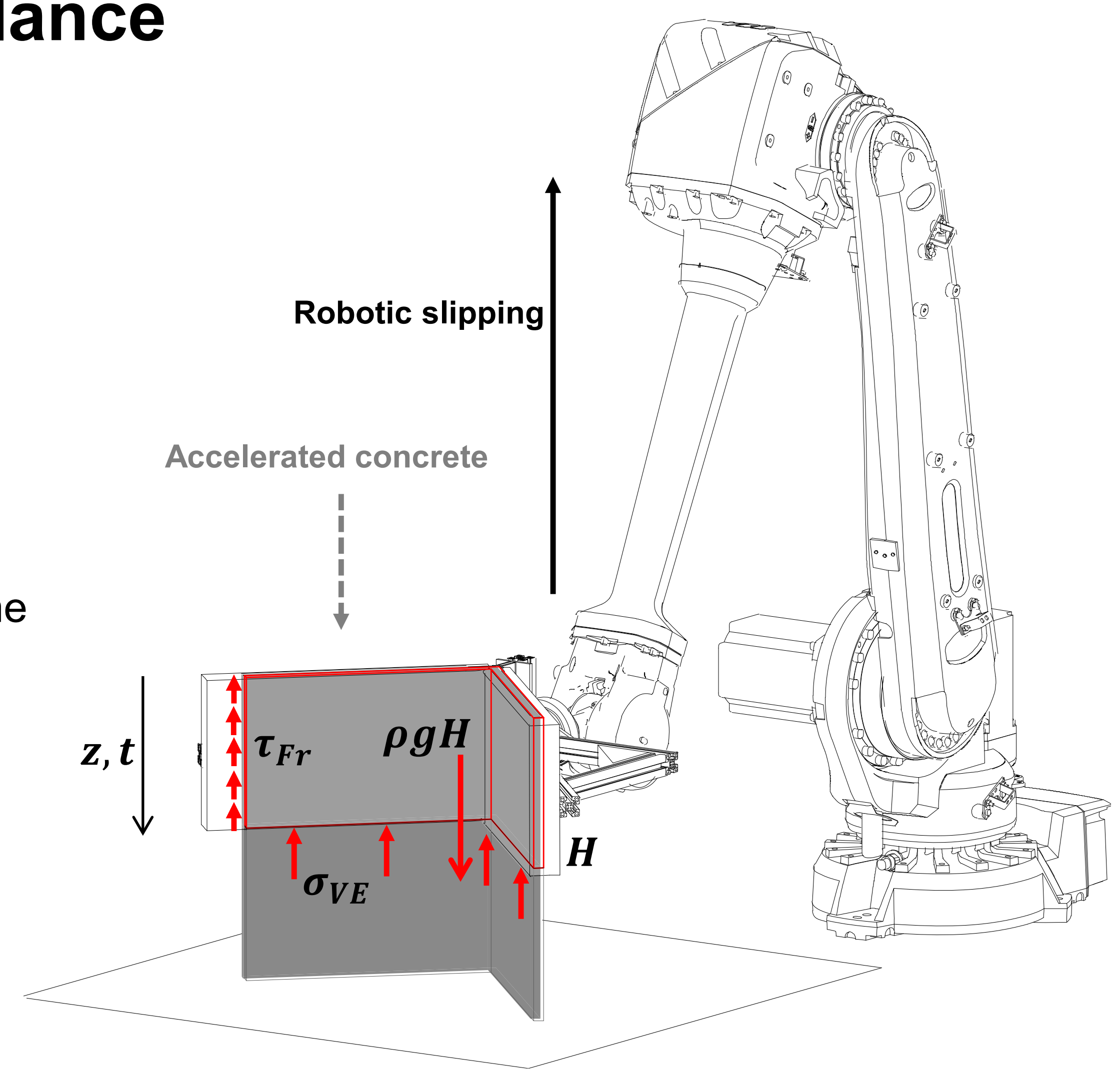
$$\tau_{Fr}(t) = \alpha_{Fr} \boxed{\tau_0(t)} = \alpha_{Fr} \boxed{\alpha_C t^{\beta_C}}$$



# Slipforming process model – force balance

Force balance: $\sigma_{VE} = \rho g H - \frac{2}{r_{hy}} \int_0^z \tau_{Fr}(z)\, dz$

Friction force: $\tau_{Fr}(t) = \alpha_{Fr}\, \tau_0(t) = \alpha_{Fr} \alpha_C t^{\beta_C}$

$$\sigma_{VE} = \rho g H - \frac{2}{r_{hy}} \int_0^{t_{Extr}} \tau_{Fr}(t) v\, dt$$

$$\sigma_{VE} = \rho g H - \frac{2 v \alpha_{Fr} \alpha_C}{r_{hy}(1+\beta_C)} {t_{Extr}}^{1+\beta_C}$$

$$\boldsymbol{\sigma_{VE} = \rho g H - \frac{H \alpha_{Fr}}{r_{hy}(1+\beta_C)} \tau_0(t_{Extr})}$$

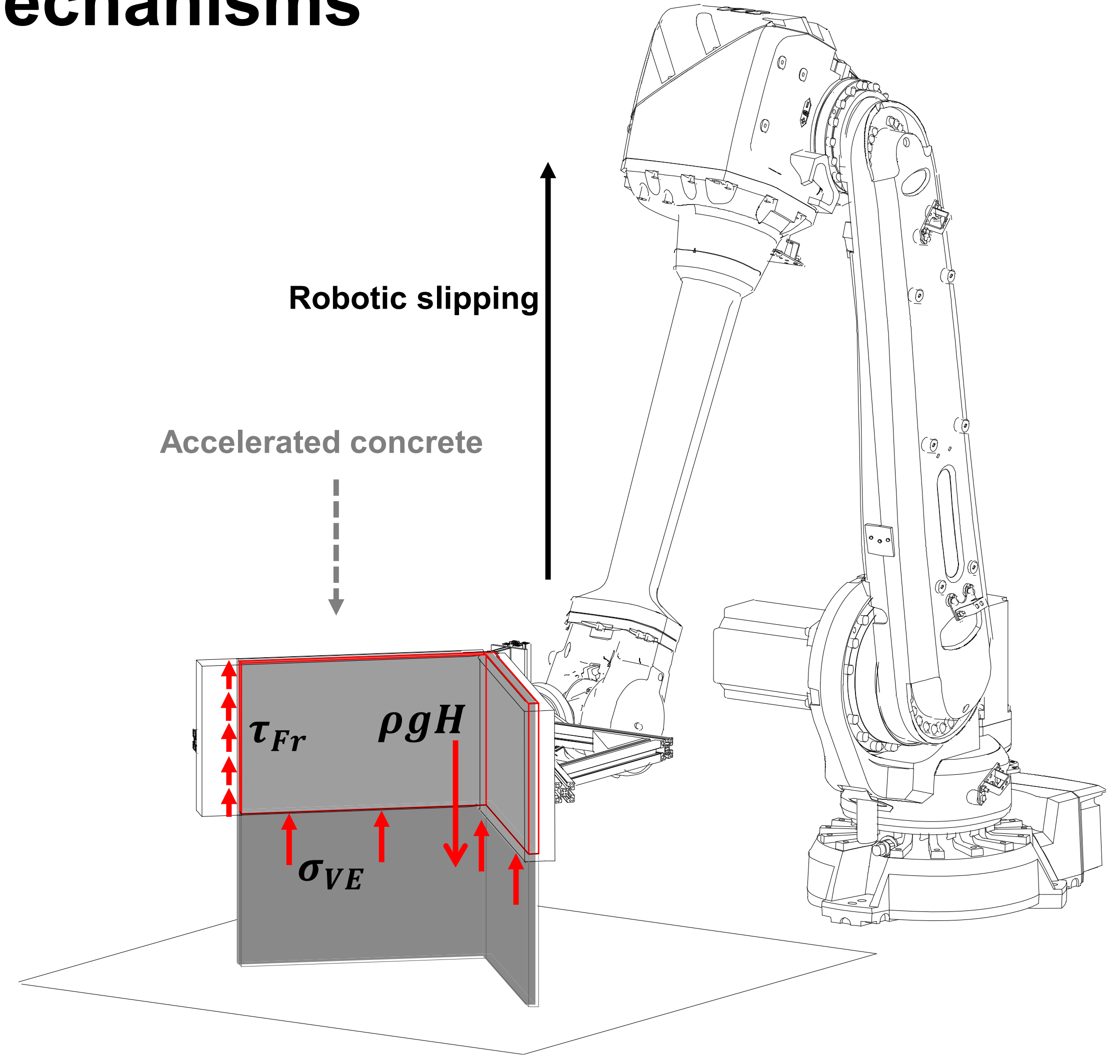
**Global frictional parameter**

# Slipforming process model – failure mechanisms

Vertical stress $\sigma_{VE}$ at the extrusion line:

- Positive
- Tresca criterion


$$0 \leq \sigma_{VE} \leq 2\tau_0(t_{Extr})$$



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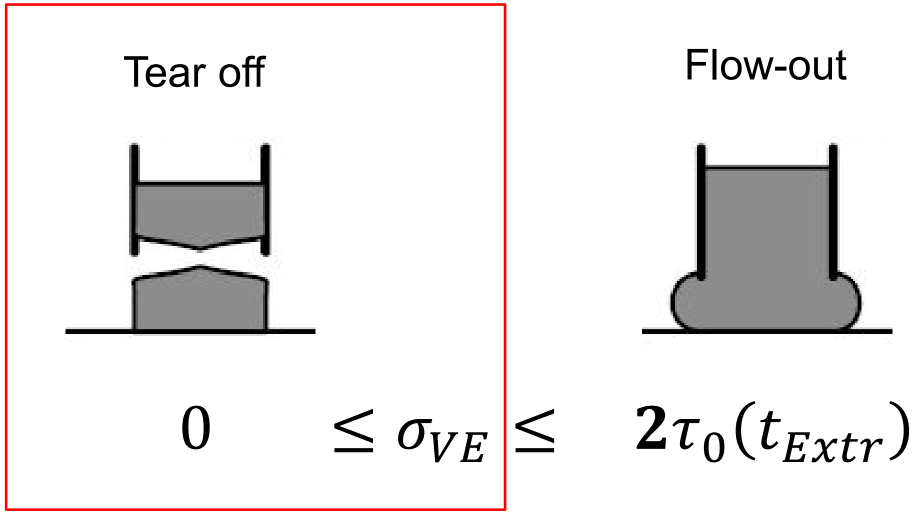
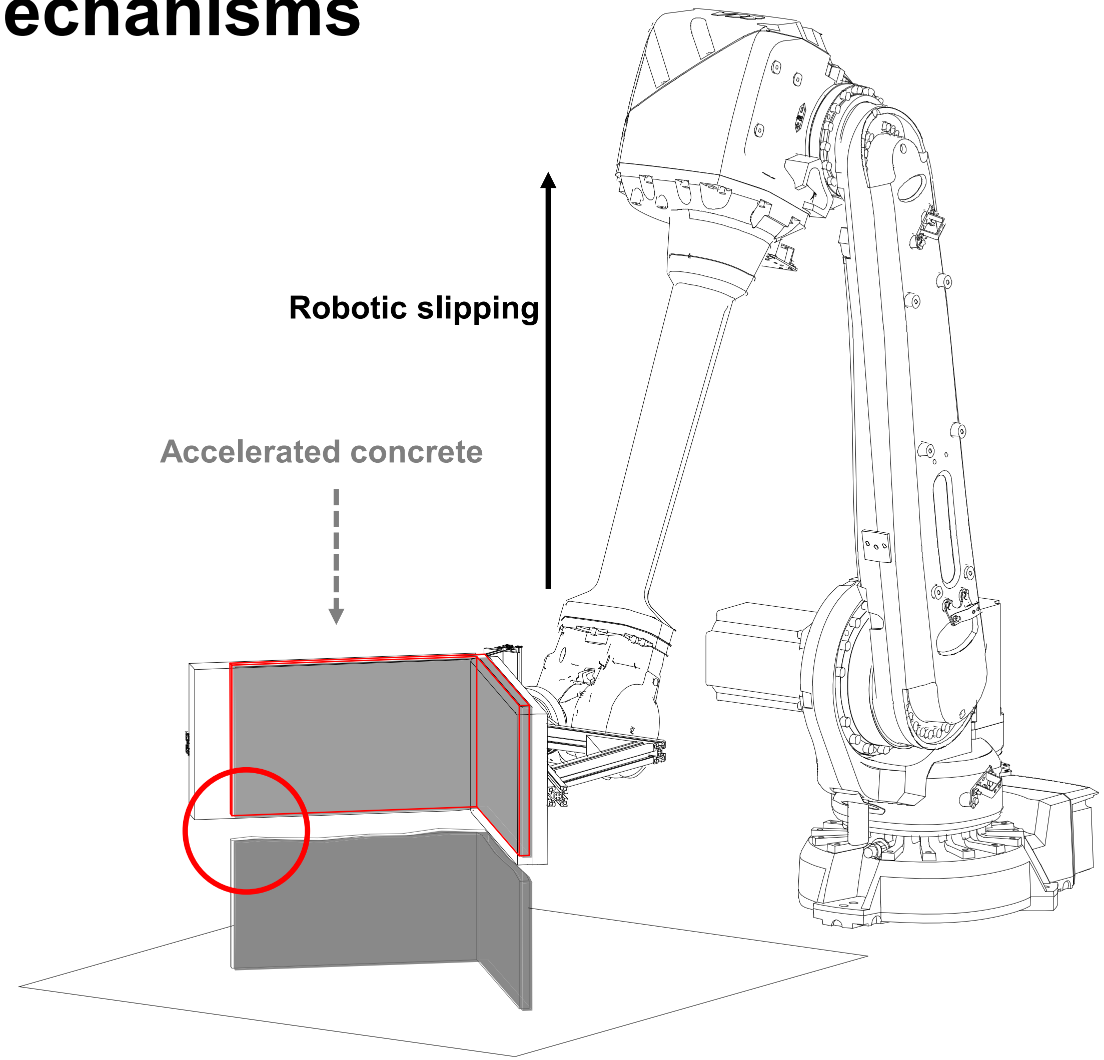



$$0 \leq \sigma_{VE} \leq 2\tau_0(t_{Extr})$$



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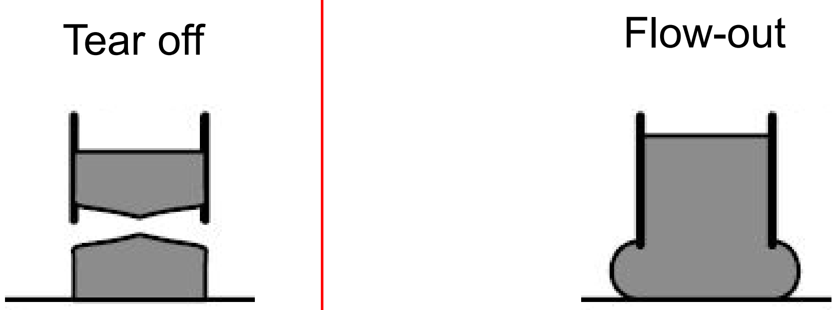


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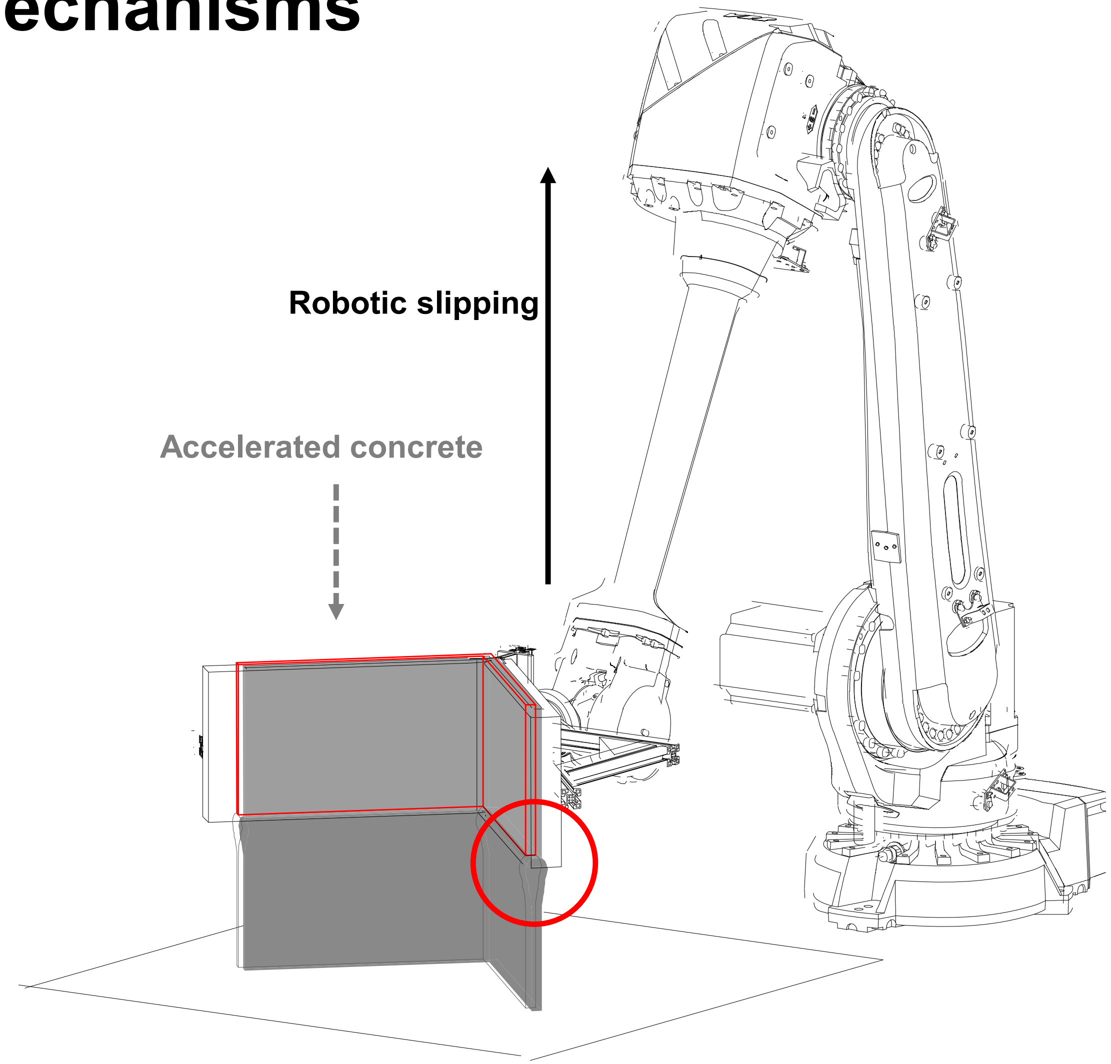

# Slipforming process model – process window

Vertical stress: $\sigma_{VE} = \rho g H - \frac{H \alpha_{Fr}}{r_{hy}(1+\beta_C)} \tau_0(t_{Extr})$

Failure criteria: $0 \leq \sigma_{VE} \leq 2\tau_0(t_{Extr})$

**Process window:** $\frac{\boldsymbol{H \alpha_{Fr}}}{\boldsymbol{r_{hy}(1+\beta_C)}} \leq \frac{\boldsymbol{\rho g H}}{\boldsymbol{2\,\tau_0(t_{Extr})}} \leq \boldsymbol{1} + \frac{\boldsymbol{H \alpha_{Fr}}}{\boldsymbol{r_{hy}(1+\beta_C)}}$

**Global frictional parameter**

# Slipforming process model – limits

**Process window:** $$\frac{H\alpha_{Fr}}{r_{hy}(1+\beta_C)} \leq \frac{\rho g H}{2\,\tau_0(t_{Extr})} \leq 1 + \frac{H\alpha_{Fr}}{r_{hy}(1+\beta_C)}$$

Negligible surface compared to volume

$r_{hy} \rightarrow \infty$

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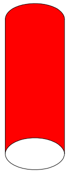

$r_{hy,c}$ = 75mm

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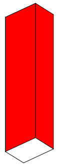

$r_{hy,m}$ = 41mm

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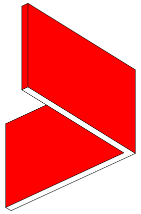


$r_{hy,f}$ = 25mm

>

Negligible volume compared to surface

$r_{hy} \rightarrow 0$

$$0 \leq \frac{\rho g H}{2\,\tau_0(t_{Extr})} \leq 1$$

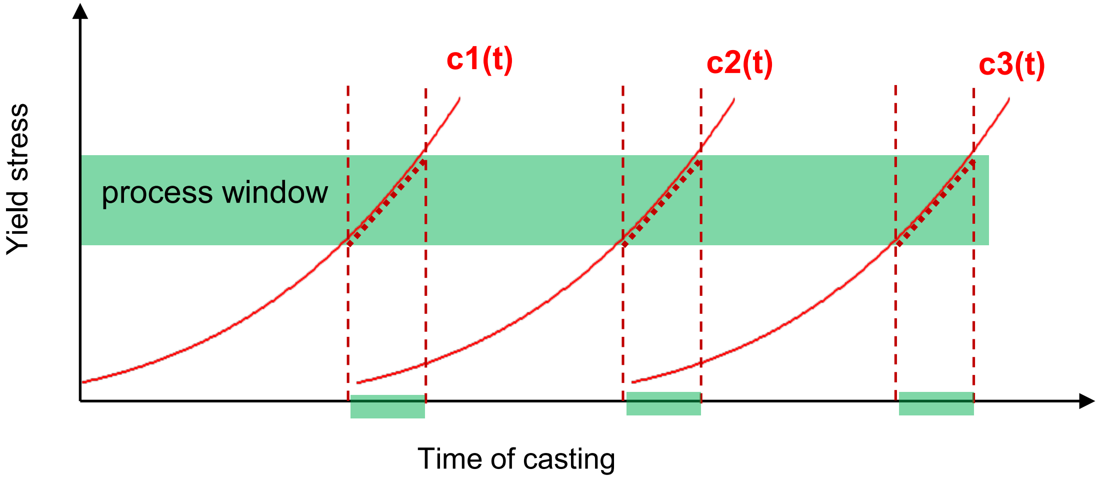
$$\infty \leq \frac{\rho g H}{2\,\tau_0(t_{Extr})} \leq \infty$$

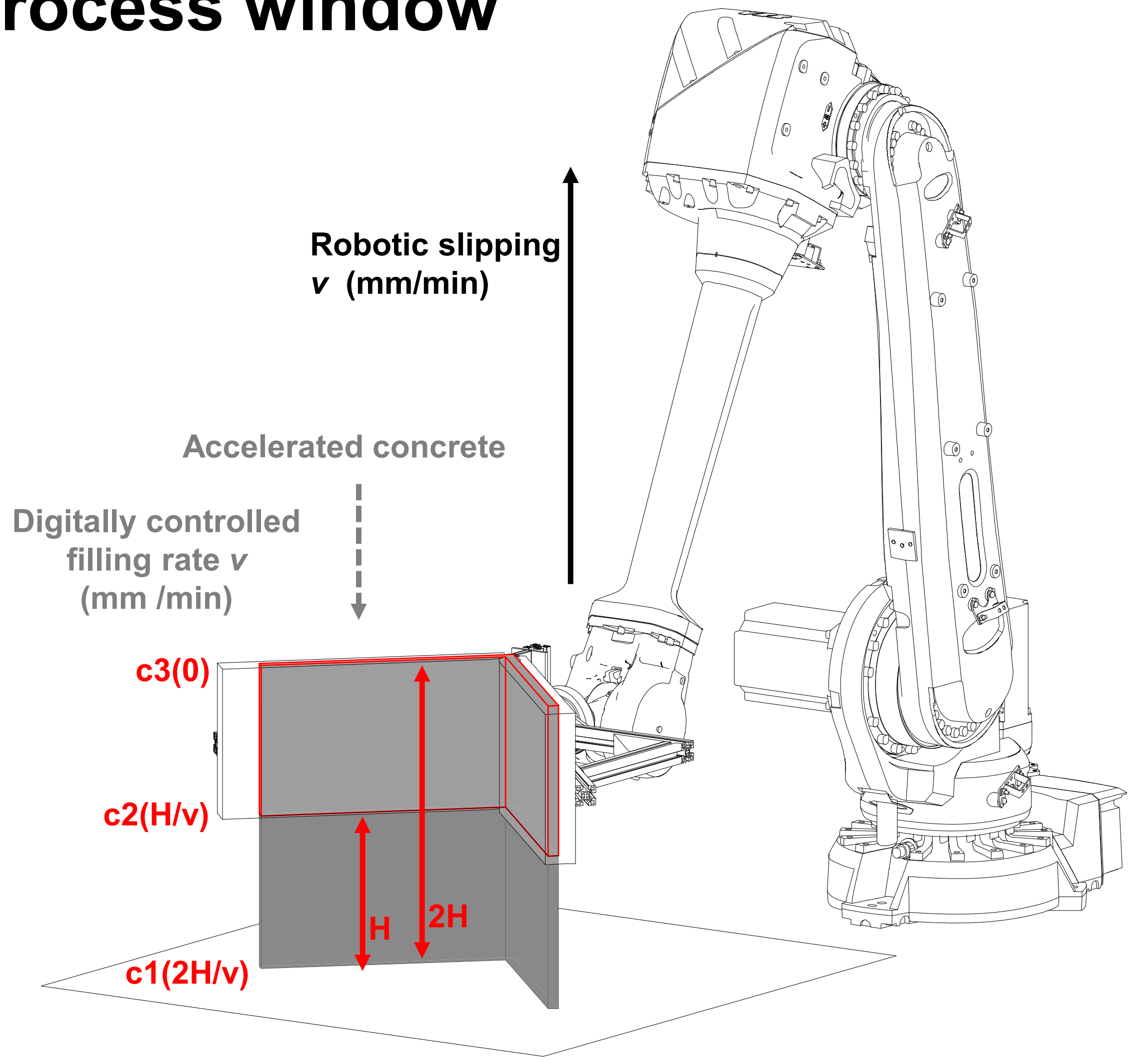
**Only sufficient strength required** ⟶ **Process impossible!**

# Results with empirical approach

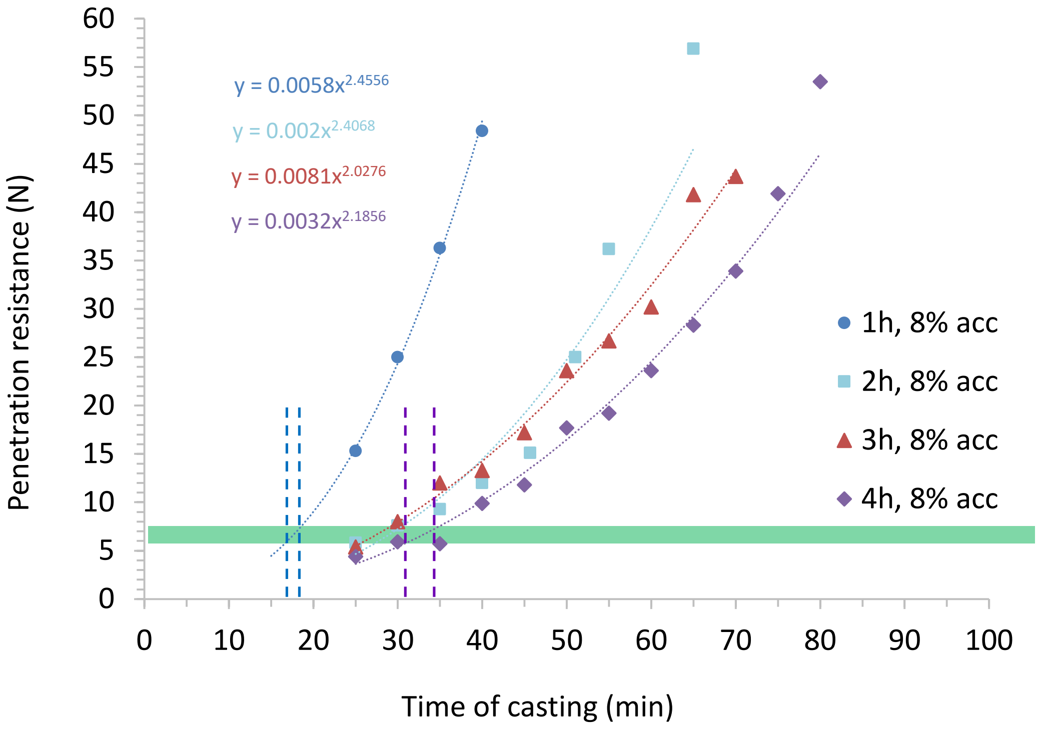
# Material requirements with narrow process window

- Uniform yield stress evolution over time
- Low slope in process window
- Extended time with target yield stress



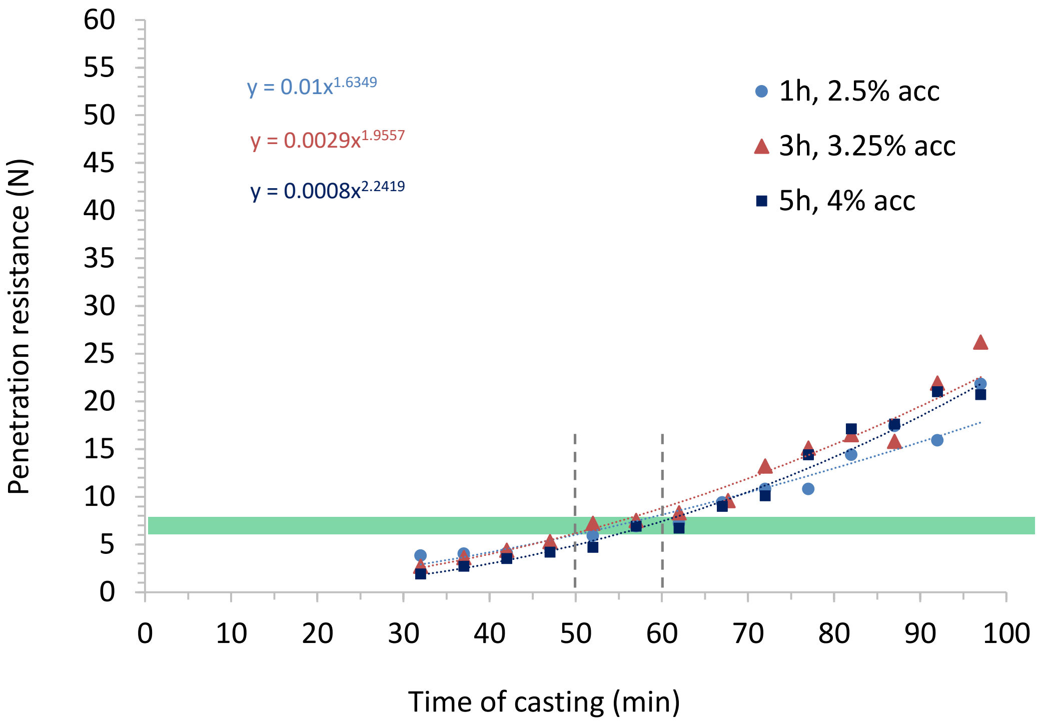



# Material adjustments




SDC_NEST Mix

# Material adjustments




SDC FoldedStructures_1 Mix


ABB
ETH zürich
ABB
WÄLTI
BAUMASCHINEN AG

# Conclusion and outlook

- Folded structures are underused
- Theoretical slipforming process model with mathematical basis instead of fully empirical approach
- The process window for thin folded structures is smaller than in previous SDC experiments
- Material adjustments were necessary to overcome the processing difficulties
- The adjusted composition and processing were validated by robotic experiments

Further improvements:

- Online feedback for the slipping process
- Changes affecting the global parameter for fiction $\frac{H\alpha_{Fr}}{r_{hy}(1+\beta_C)}$

# Thank you for your attention!