DIANA Seminar

Constitutive Model for the Non-linear Cyclic Behavior of Brick Masonry

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June 14th 2023

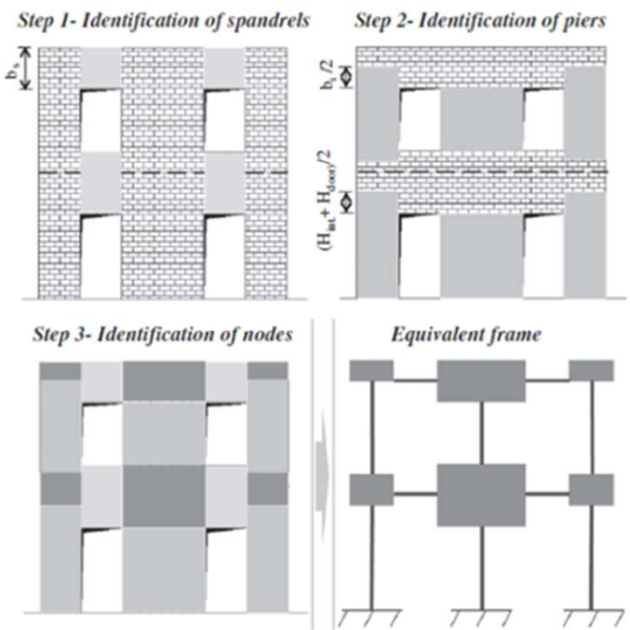
Overview

- ❑Background
- ❑Description of constitutive model
- ❑Validation against experiments
- ❑Comparison with existing models
- ❑Conclusions

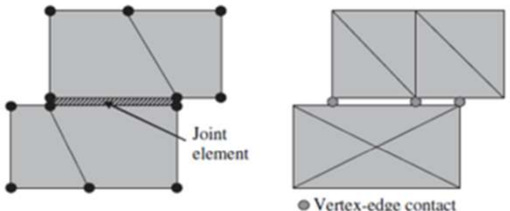
Background

Approaches for numerical modelling of masonry

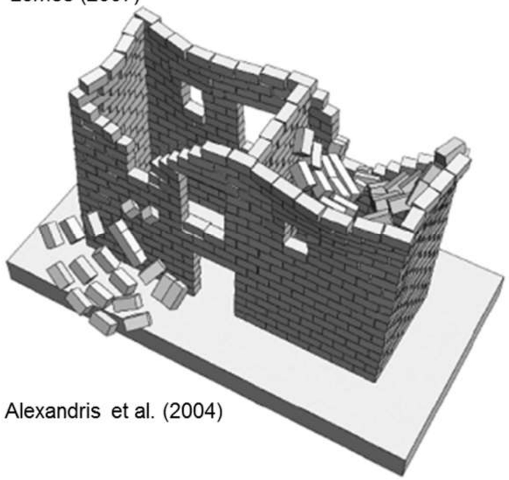
- **Macro-element Based Methods**
- **Discrete Element Method**
- **Finite Element Method**
  - Detailed Micro-modelling
  - Simplified Micro-modelling
  - Macro-modelling



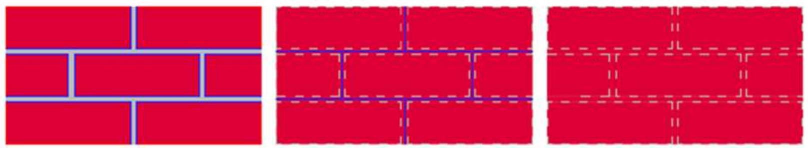
Lagomarsino et al (2013)

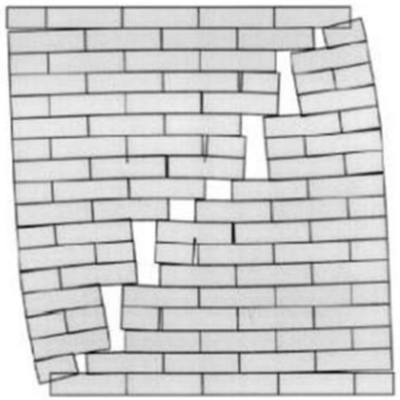


Lemos (2007)

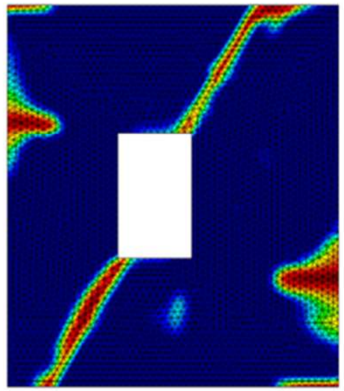


Alexandris et al. (2004)



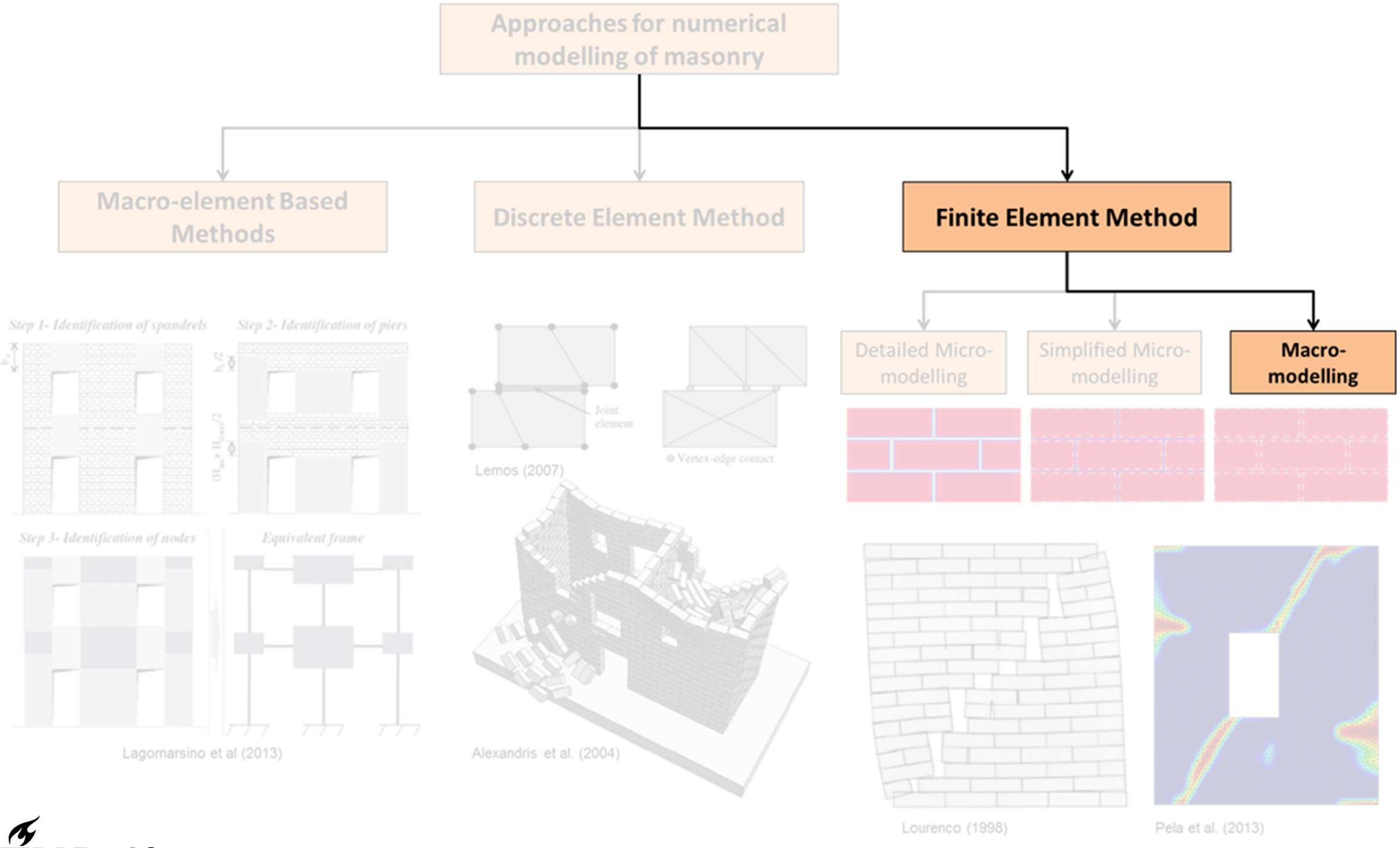


Lourenco (1998)



Pela et al. (2013)

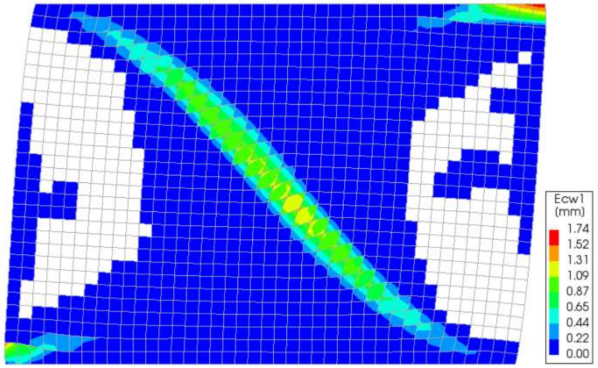
Background

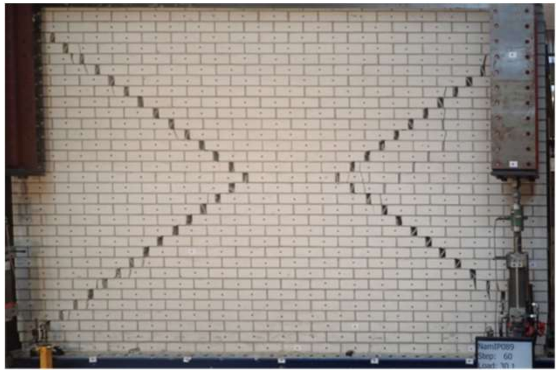


TU Delft

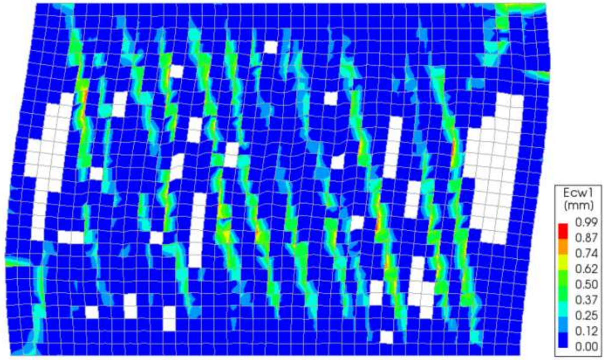
Background

TSRCM



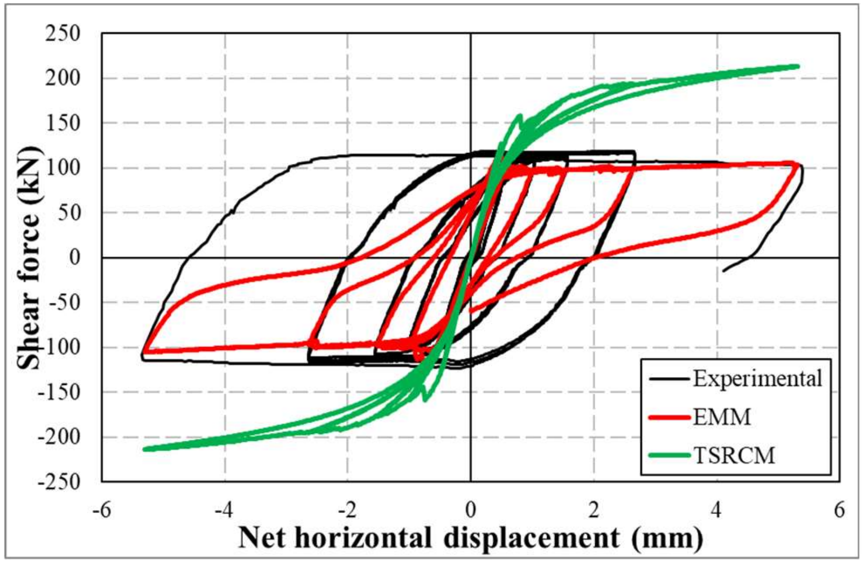


EMM



(σ_1, σ_2)

+ Damage localization
- Capacity overestimation
- Energy dissipation



$(\sigma_{xx}, \sigma_{yy}, \tau_{xy})$

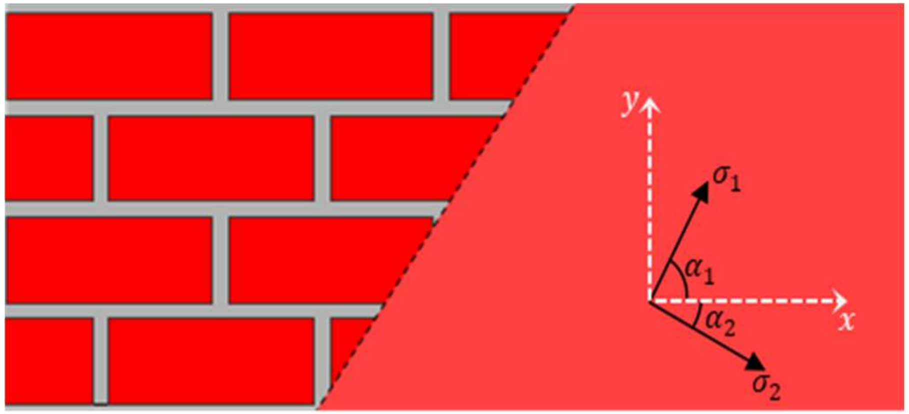
- Damage localization
+ Capacity estimation
+ Energy dissipation

TU Delft

Model description

Orthotropic Total-Strain-Rotating-Crack Model

- ❑ Orthotropic behavior
- ❑ Material properties varying with principal angle until cracking
- ❑ Failure in tension, compression
- ❑ Tensile softening depending on cracking angle
- ❑ (Indirect) failure in shear
- ❑ 15 independent material variables



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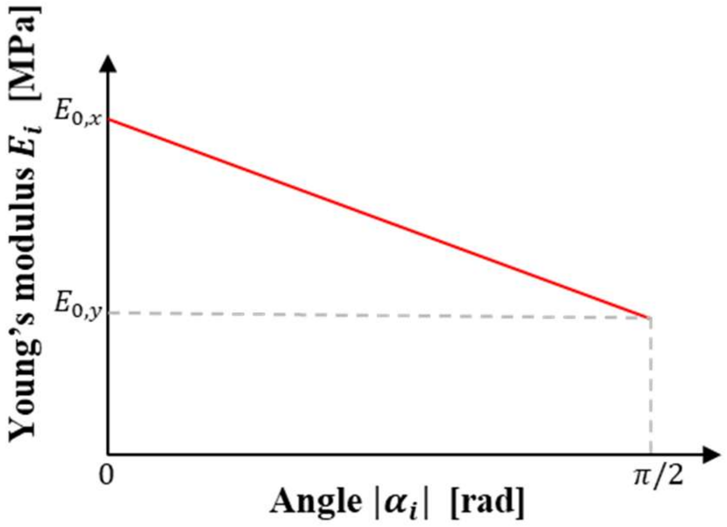
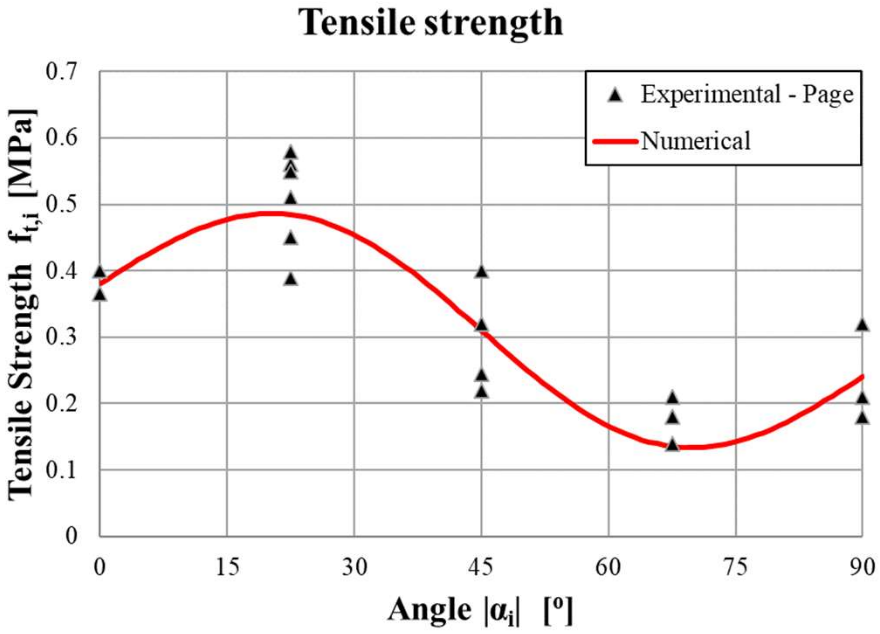
Model description

Variation of material properties





$$E_i = E_{0,x} + \left(E_{0,y} - E_{0,x}\right)\frac{|\alpha_i|}{\pi/2}$$

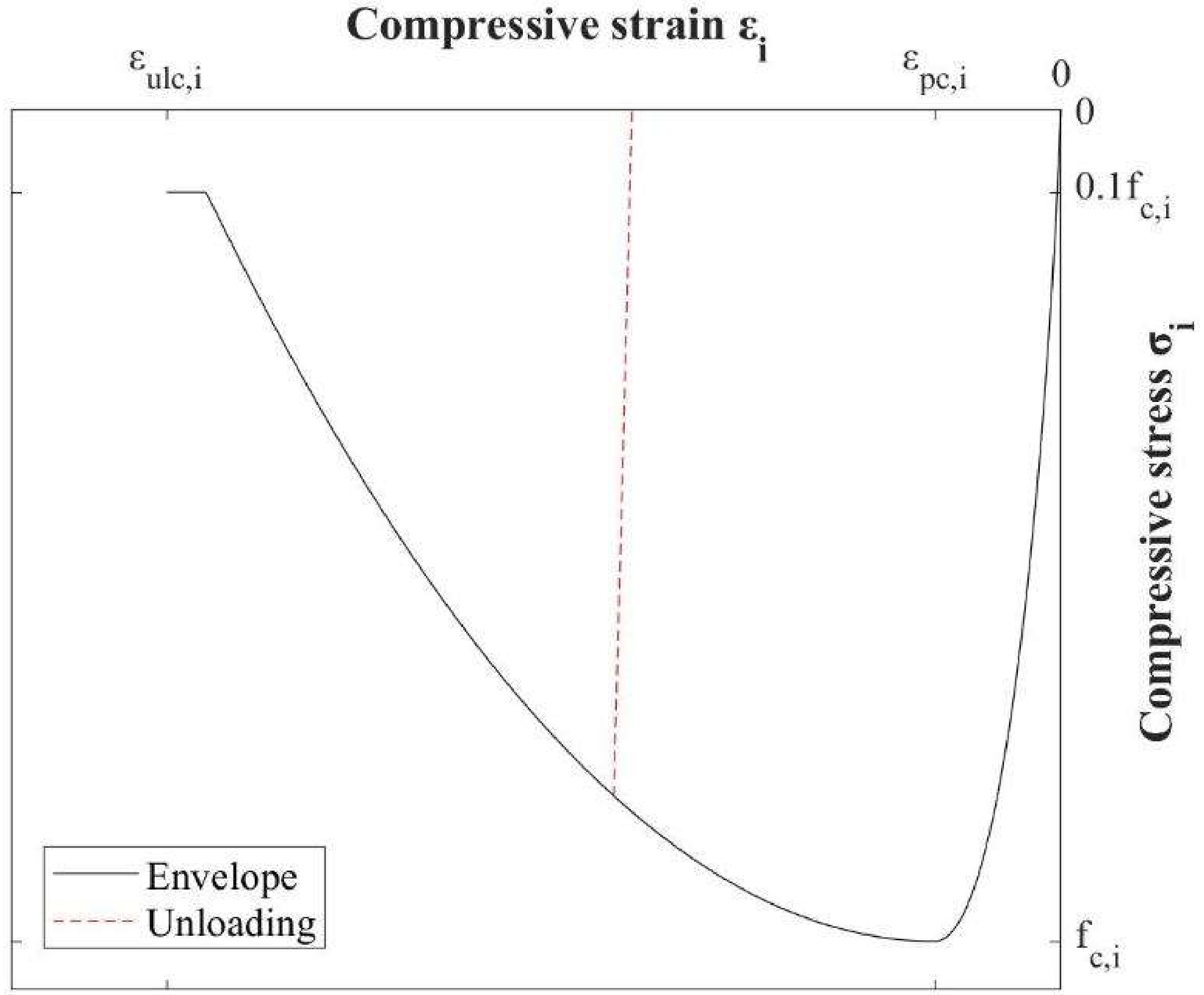
$$f_{t,i} = f_{tx} + \left(f_{ty} - f_{tx}\right)\frac{|\alpha_i|}{\pi/2} + \left(\sqrt{f_{tx}^2 + f_{ty}^2} - \frac{f_{tx} - f_{ty}}{2}\right)\sin(4|a_i|)$$

Linear variation for $E_{p,i}, f_{c,i}, G_{ft,i}, G_{fc,i}$

After cracking: material properties are fixed to those corresponding to the cracking angle a_{crack}

Model description

Compression



$$\sigma_i = \begin{cases} E_i\varepsilon_i\left[1-\frac{1}{n_i}\left(\frac{\varepsilon_i}{\varepsilon_{pc,i}}\right)^{n_i-1}\right] & for\ \varepsilon_{pc,i} \le \varepsilon_i \le 0 \\ \min\left[f_{c,i}\left[1-\left(\frac{\varepsilon_i-\varepsilon_{pci}}{\varepsilon_{ulc,i}-\varepsilon_{pc,i}}\right)^2\right];0.1f_{ci}\right] & for\ \varepsilon_{ulc,i} \le \varepsilon_i \le \varepsilon_{pc,i} \\ 0.1\,f_{c,i} & for\ \ \varepsilon_i < \varepsilon_{ulc,i} \end{cases}$$

Where $n_i = \frac{E_i}{E_i - f_{c,i}/\varepsilon_{pc,i}}$

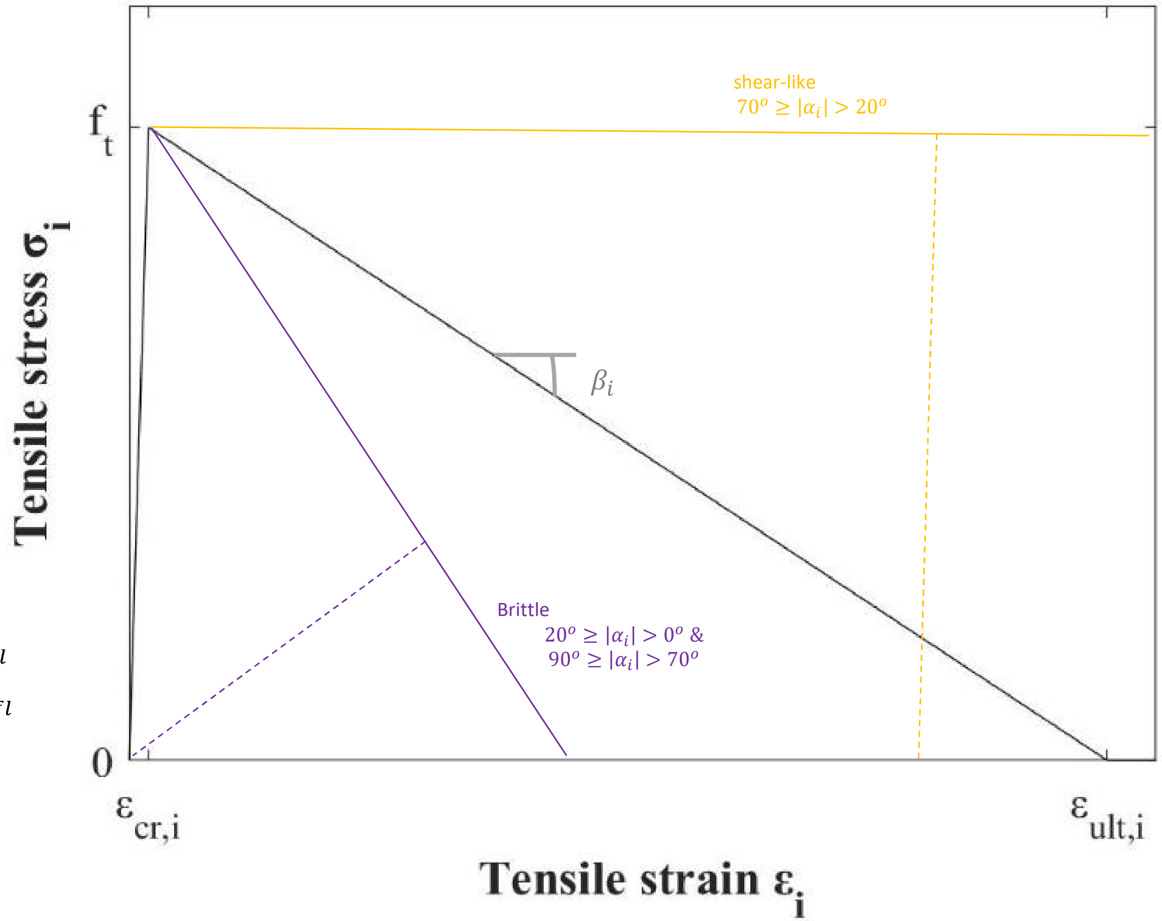
Model description

Tension

$$\sigma_i = \begin{cases} E_i \varepsilon_i & \text{for } \varepsilon_{cr,i} \geq \varepsilon_i \geq 0 \\ \max(f_{t,i}; \sigma_{un}) \left[1 - \dfrac{\varepsilon_i - \varepsilon_{cr,i}}{\varepsilon_{ult,i} - \varepsilon_{cr,i}}\right] & \text{for } \varepsilon_{ult,i} \geq \varepsilon_i \geq \varepsilon_{cr,i} \\ E_{res,i} \varepsilon_i & \text{for } \varepsilon_i > \varepsilon_{ult,i} \end{cases}$$

$$\varepsilon_{ult,i} = \begin{cases} \min\left\{\dfrac{f_{t,i}}{\beta_i} + \varepsilon_{cr,i}; 100\varepsilon_{ult,k}\right\} & \text{for } \theta_{fl} \geq |\alpha_{crack,i}| \geq 0^o \\ 100\varepsilon_{ult,k} & \text{for } 90^o - \theta_{fl} > |\alpha_{crack,i}| > \theta_{fl} \\ \min\left\{\dfrac{f_{t,i}}{\beta_i} + \varepsilon_{cr,i}; 100\varepsilon_{ult,k}\right\} & \text{for } 90^o \geq |\alpha_{crack,i}| \geq 90^o - \theta_{fl} \end{cases}$$

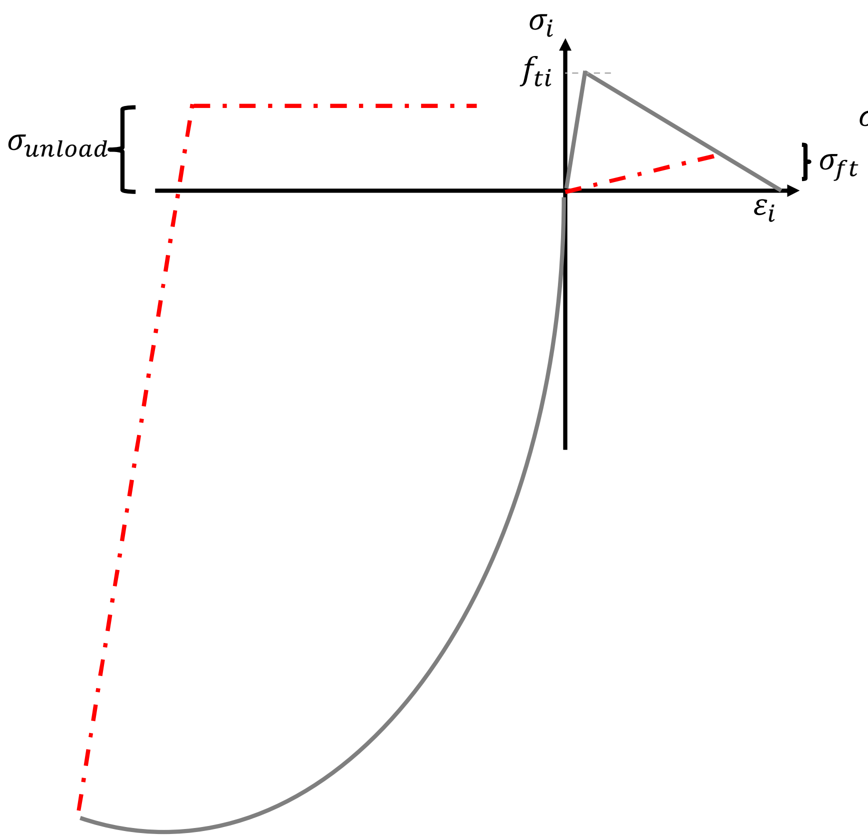
$$\beta_i = \begin{cases} \dfrac{\beta_x\left(|\alpha_{crack,i}| - \theta_{fl}\right)^2}{\theta_{fl}^2} & \text{for } \theta_{fl} \geq |\alpha_{crack,i}| \geq 0^o \\ \beta_y \sin\left(4.5\left(|\alpha_{crack,i}| - (90^o - \theta_{fl})\right)\right) & \text{for } 90^o \geq |\alpha_{crack,i}| \geq 90^o - \theta_{fl} \end{cases}$$



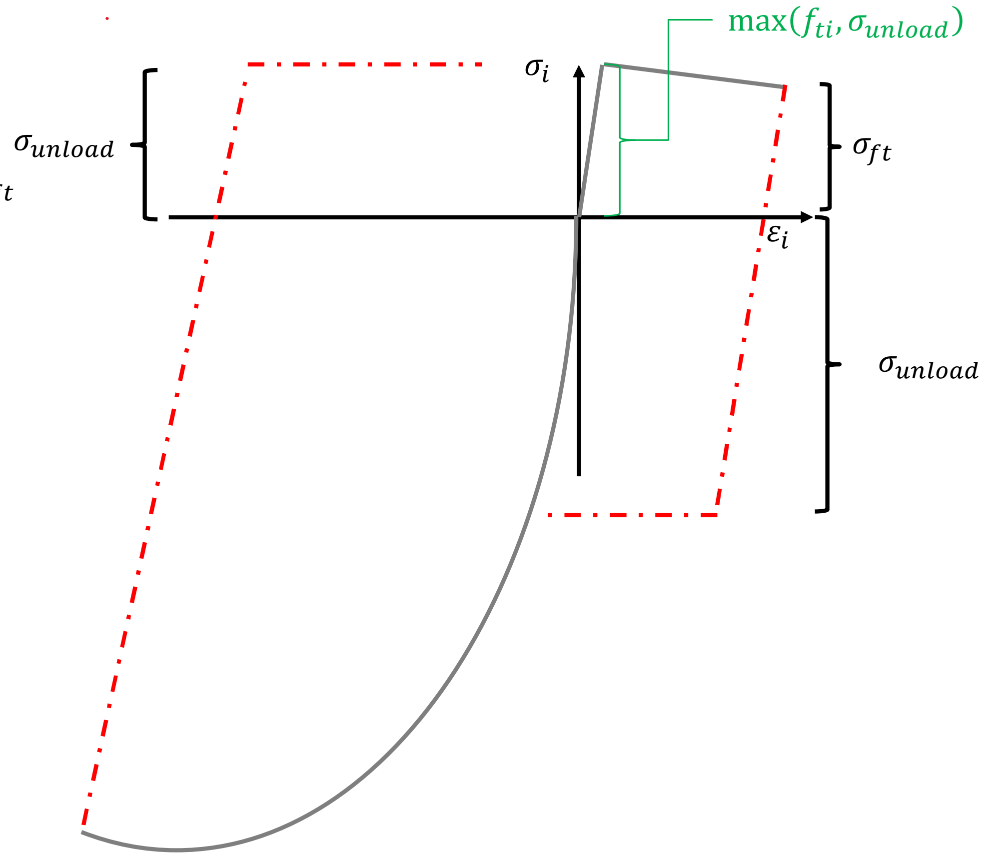
Model description

Cyclic behavior

$0^o \leq |\alpha_i| < \theta_{fl}$ &
$90^o - \theta_{fl} < |\alpha_i| < 90^o$



$\theta_{fl} \leq |\alpha_i| \leq 90^o - \theta_{fl}$

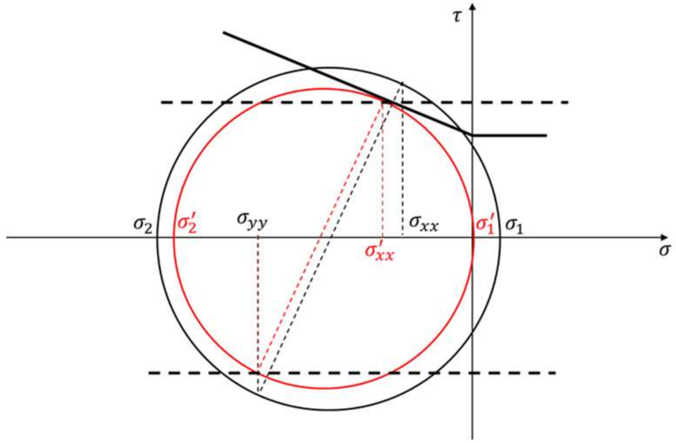


$$\sigma_{unload} = \max(\sigma_{ft}, \tau_{max})$$

$$\tau_{max} = \max\left(c_o, c_0 - \tan\phi\left(\sigma_{yy0} + E_y \cdot \delta\varepsilon_{yy}\right)\right)$$

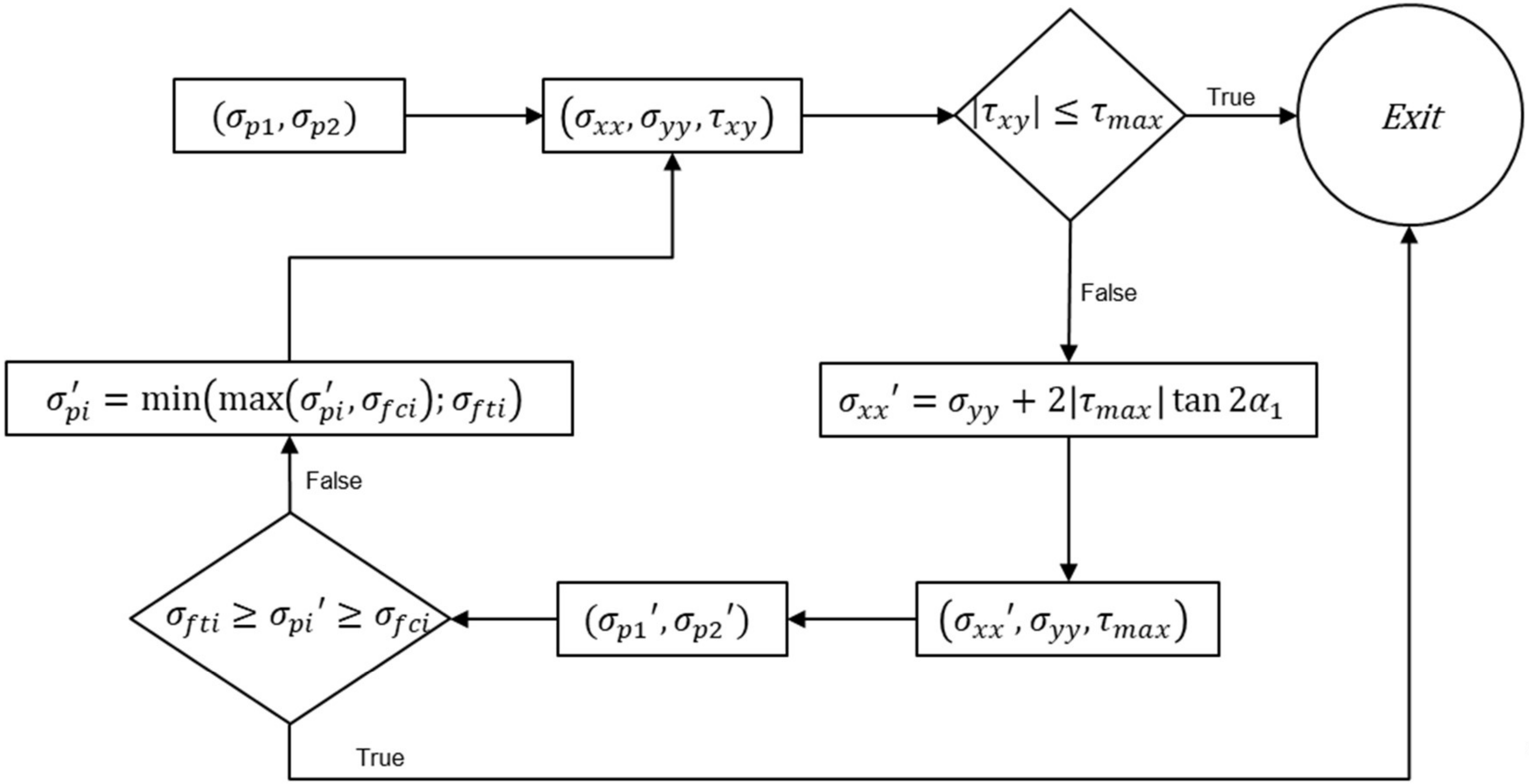
TU Delft

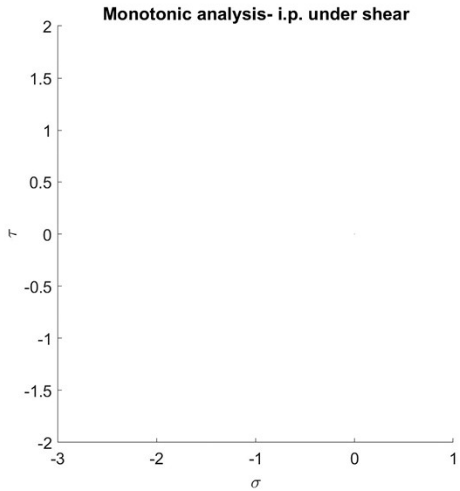
Model description



Shear limitation

- Coaxiality of $\sigma_i - \varepsilon_i$
- $\tau_{max} = \max\left(c_o, c_0 - \tan\phi\left(\sigma_{yy0} + E_y \cdot \delta\varepsilon_{yy}\right)\right)$





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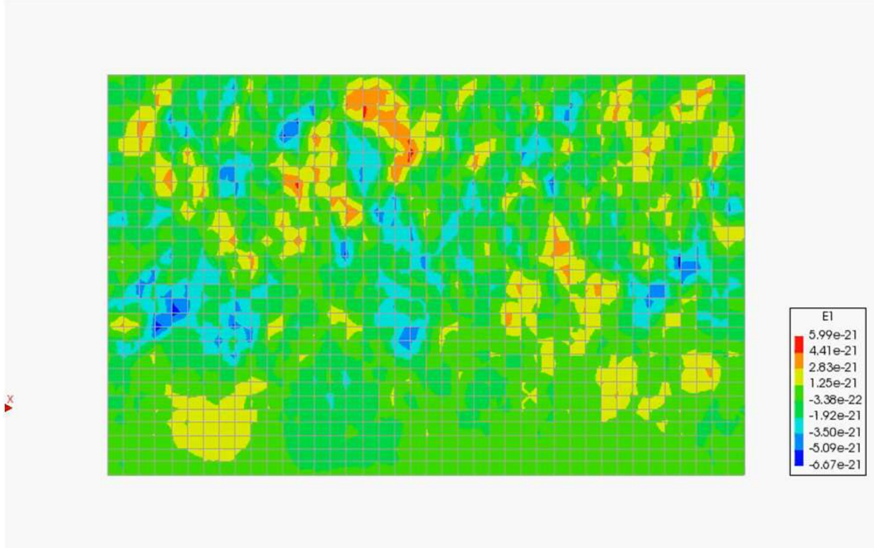
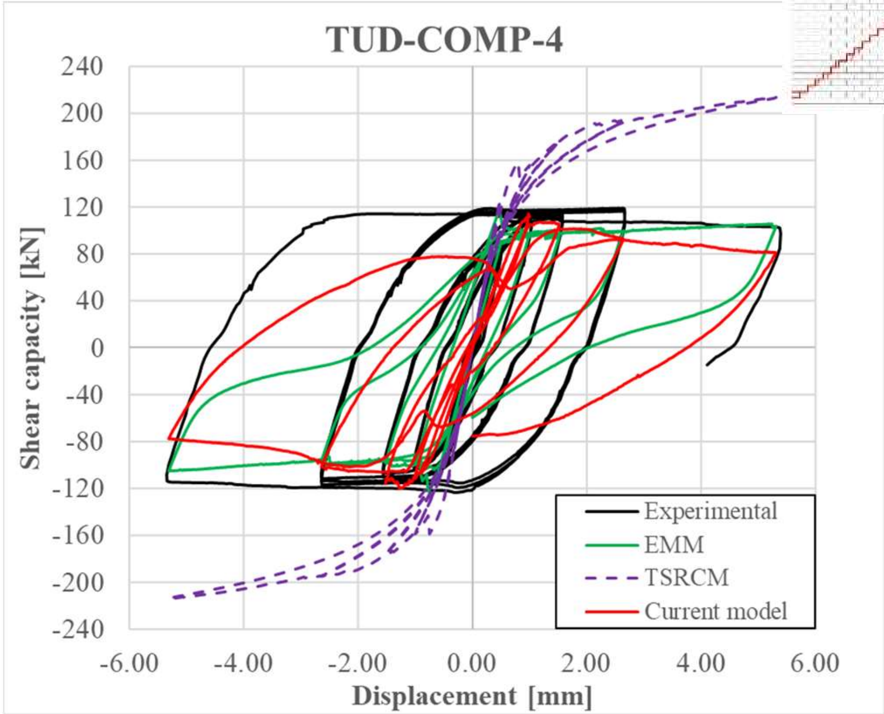
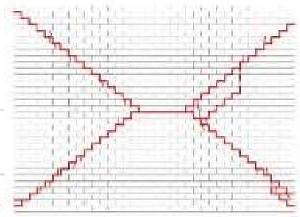
Validation

TUD_COMP_4

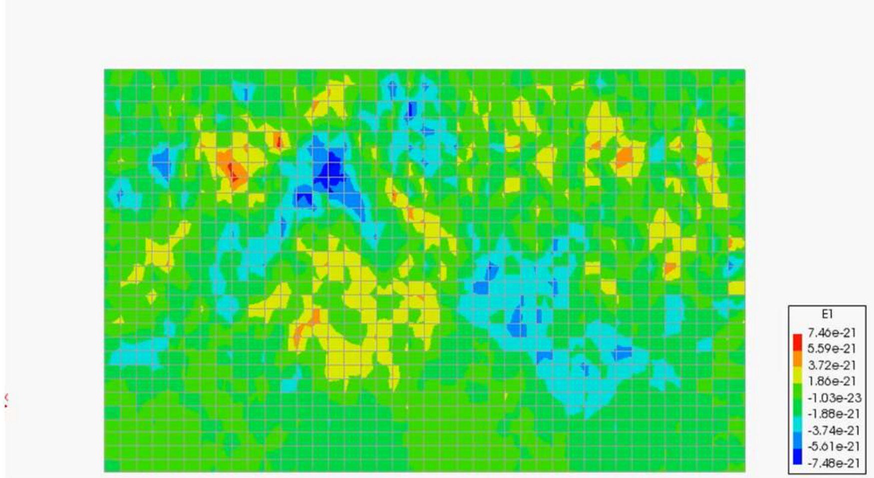
EMM



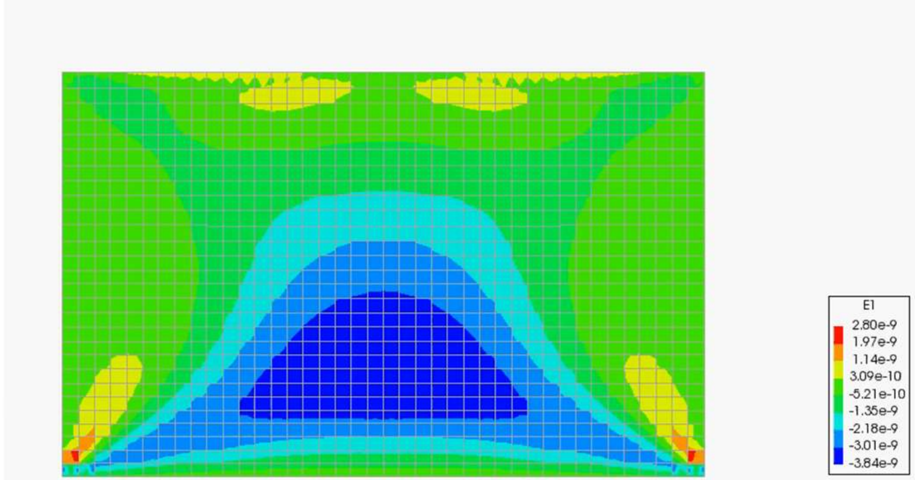




TSRCM



Current model

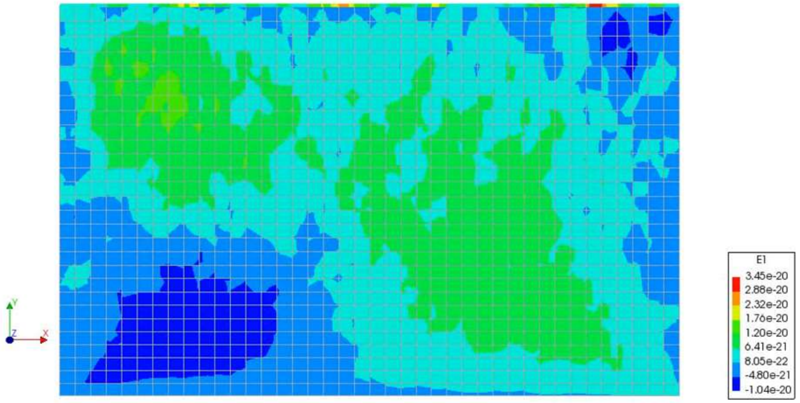


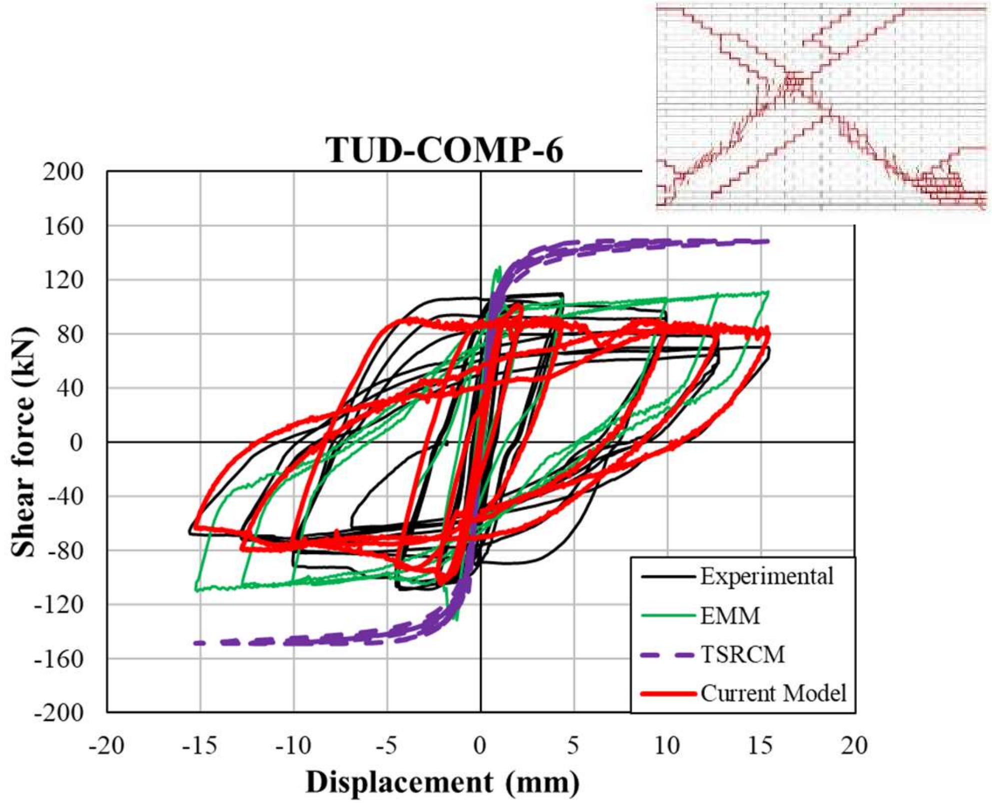
TU Delft

Validation

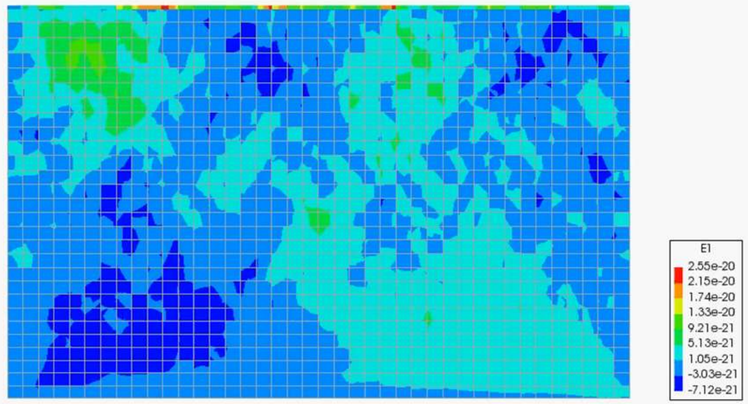
TUD_COMP_6

EMM

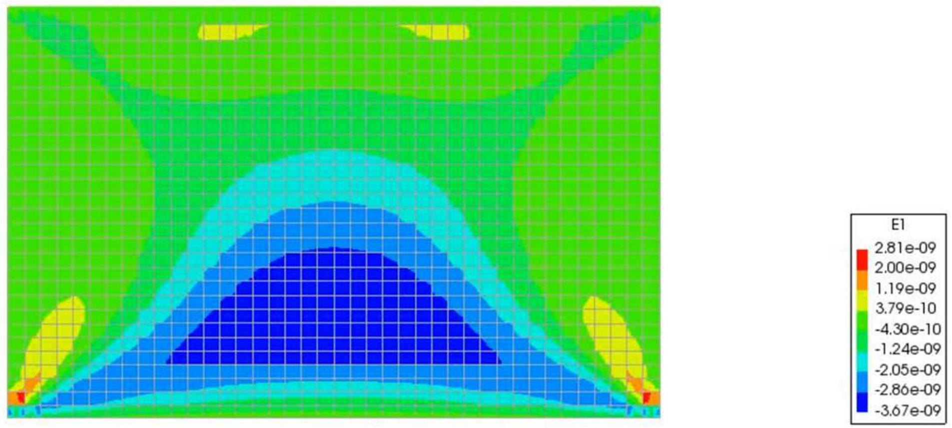




TSRCM



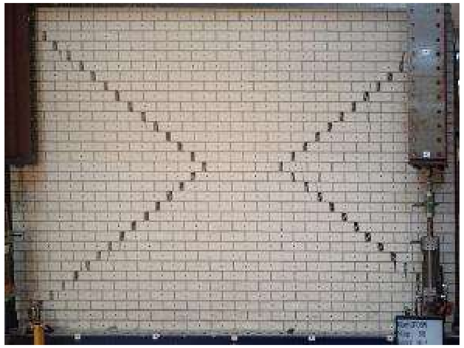
Current model

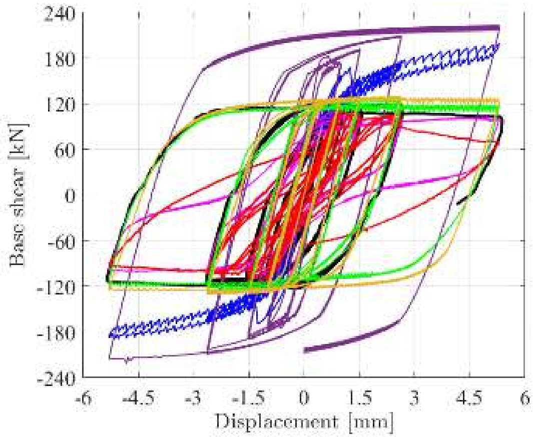


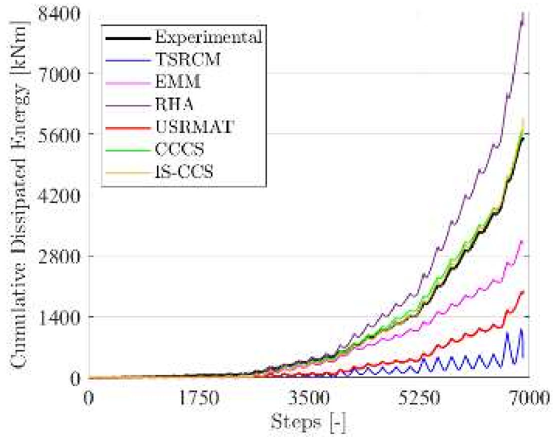
TUDelft

Comparison with other existing models

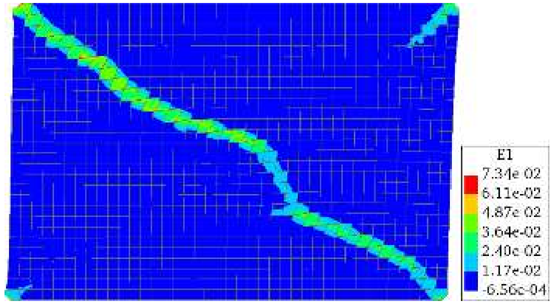
TUD_COMP_4



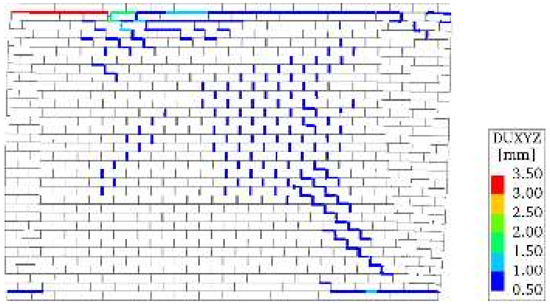




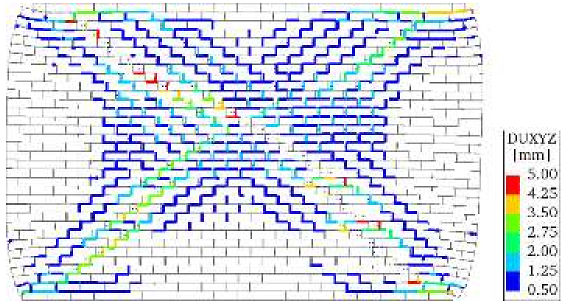
Current model



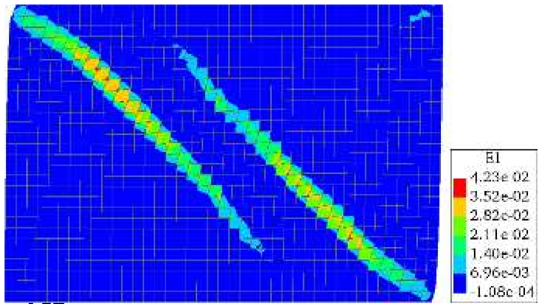
Micro-IS-CCS



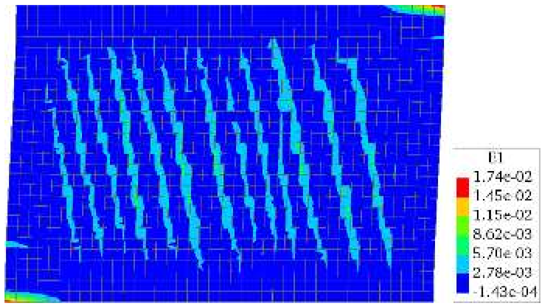
Micro-CCCS (Lourenco)



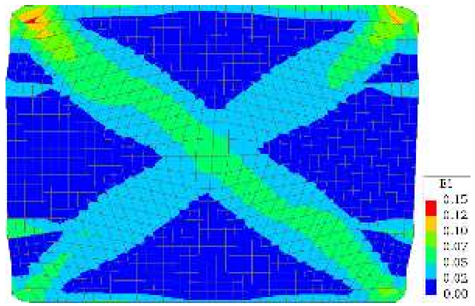
TSRCM



EMM



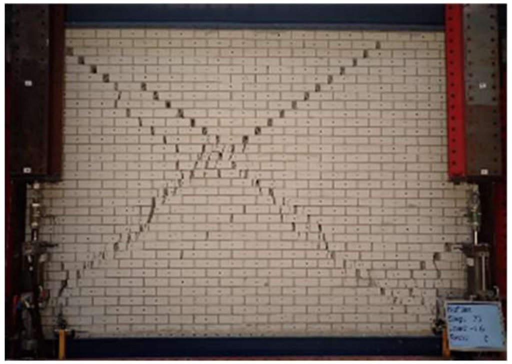
Rankine Hill Anisotropy

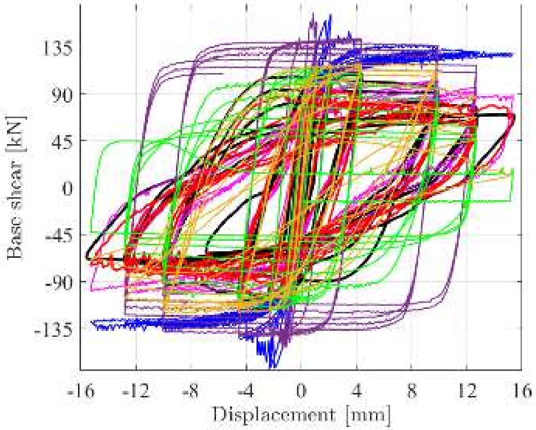


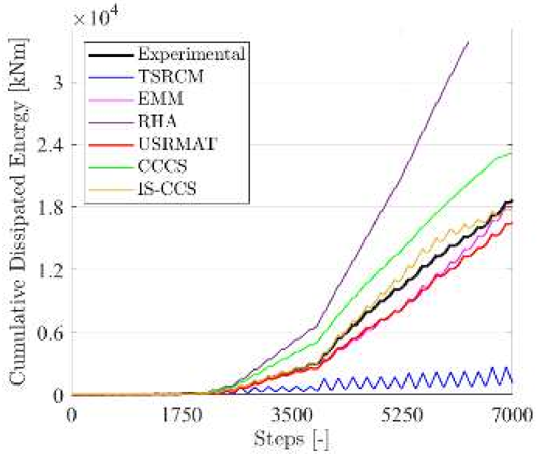
TUDelft

Comparison with other existing models

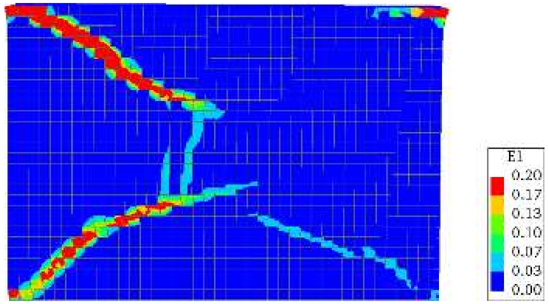
TUD_COMP_6



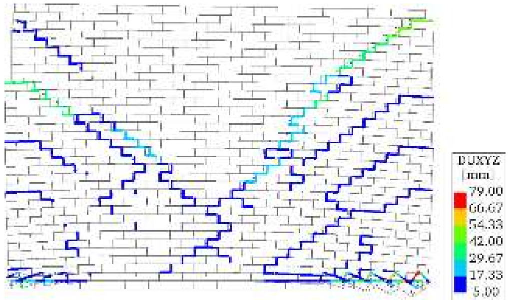




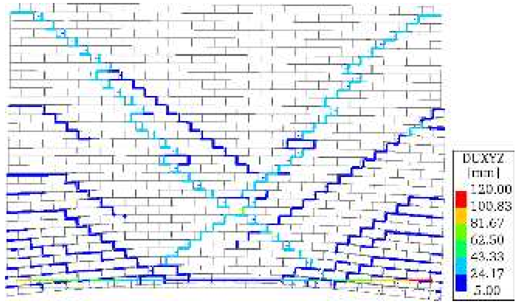
Current model



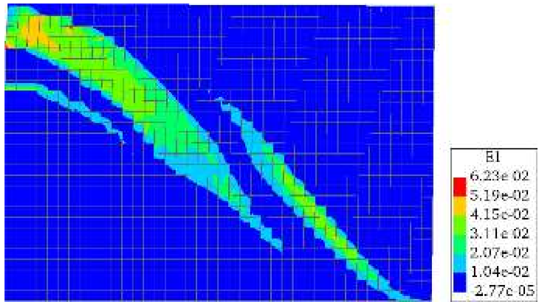
Micro-IS-CCS



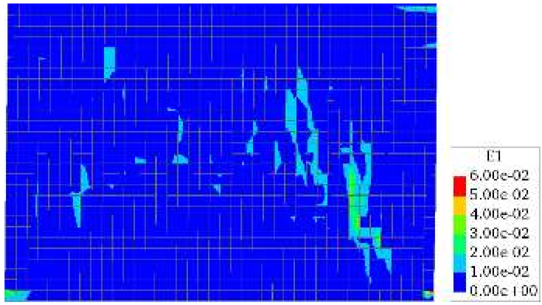
Micro-CCCS (Lourenco)



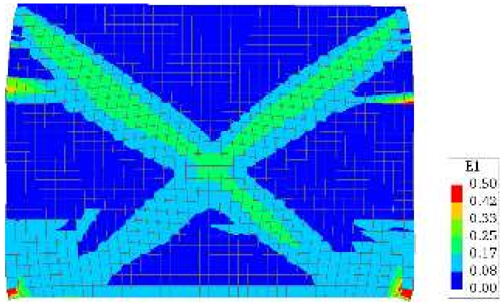
TSRCM



EMM



Rankine Hill Anisotropy

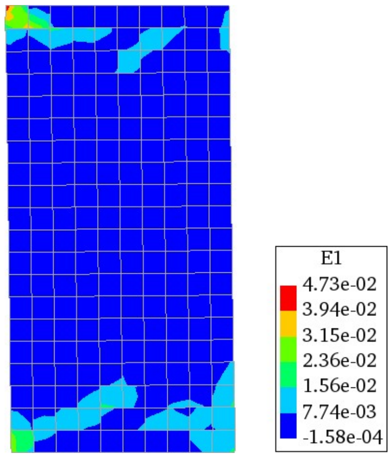


TUDelft

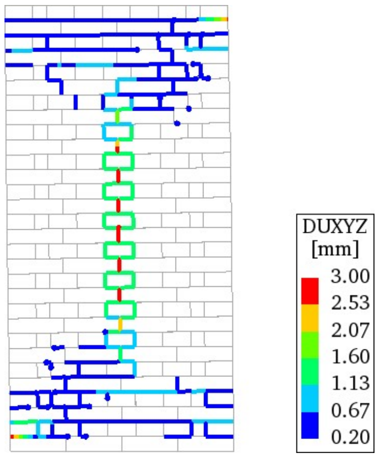
Comparison with other existing models

HIGSTA

Current model



Micro-IS-CCS



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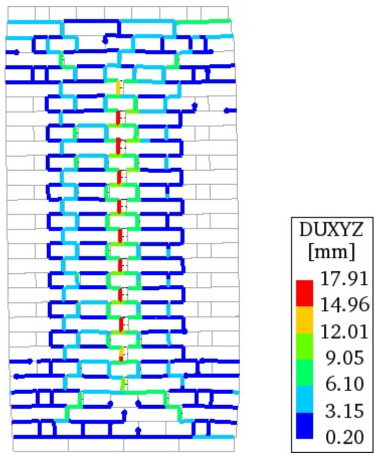
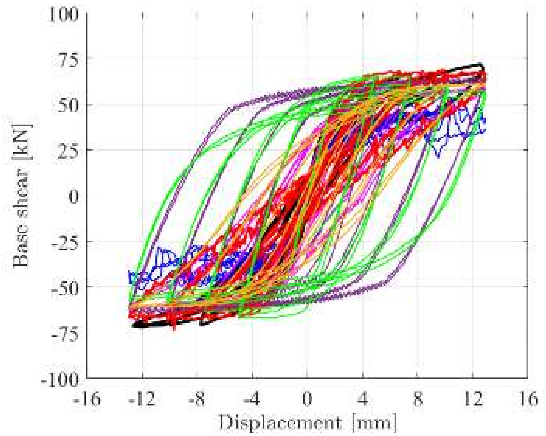
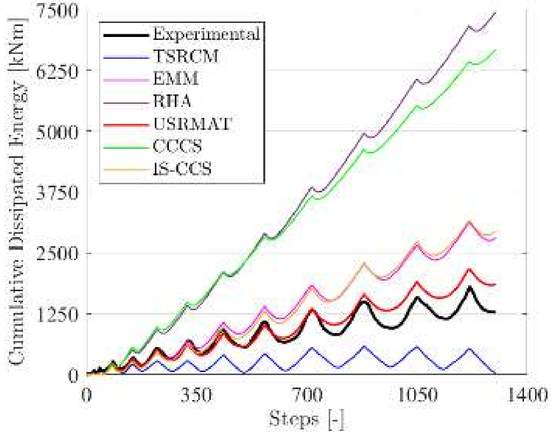
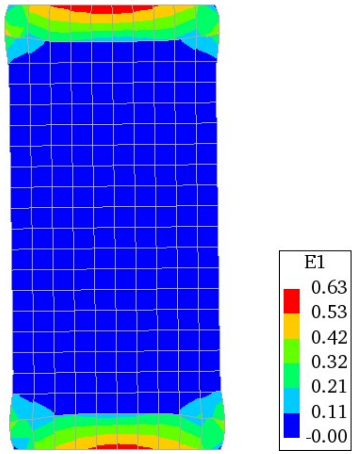


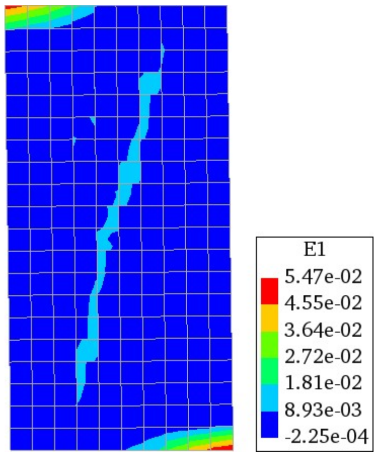




TSRCM



EMM



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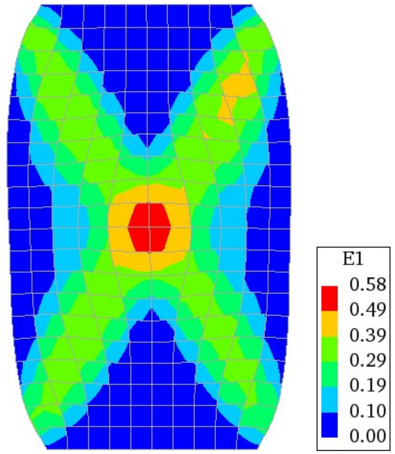
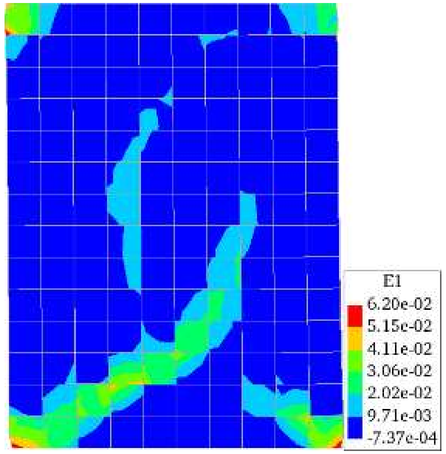


TU Delft

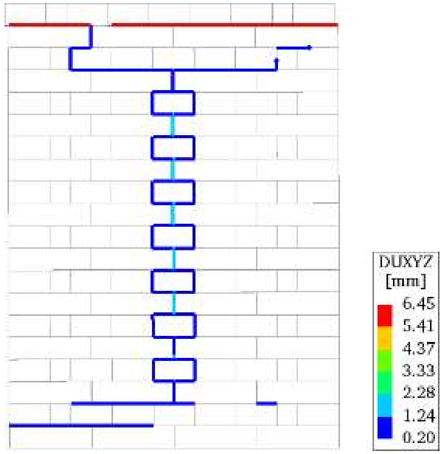
Comparison with other existing models

LOWSTA

Current model



Micro-IS-CCS



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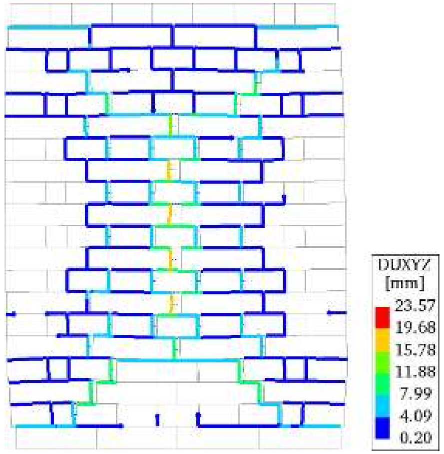

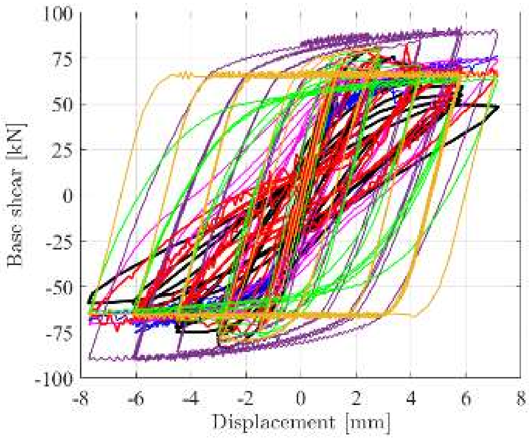

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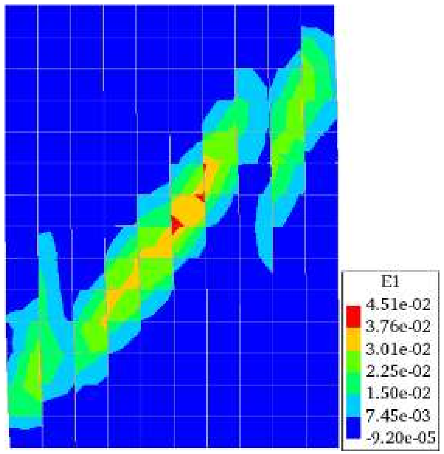
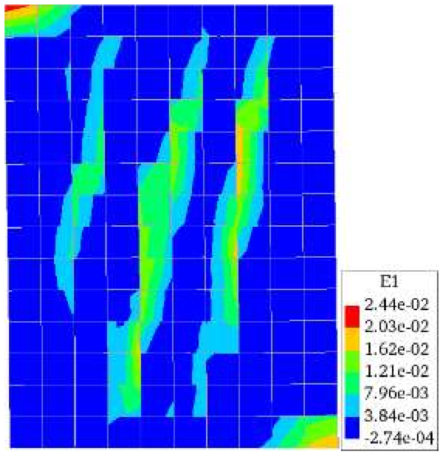
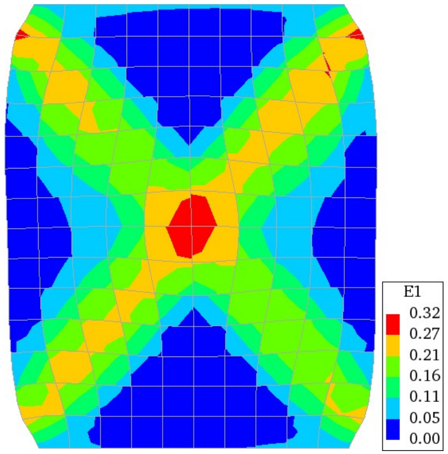
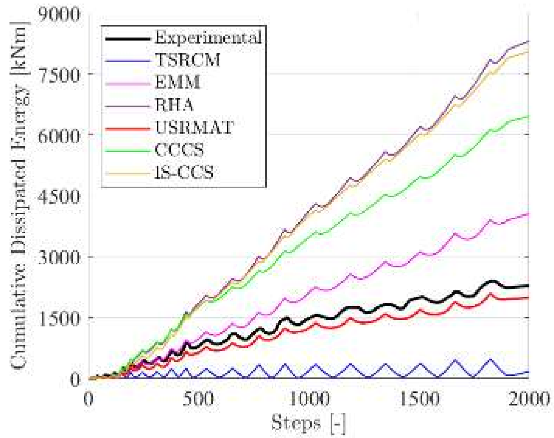


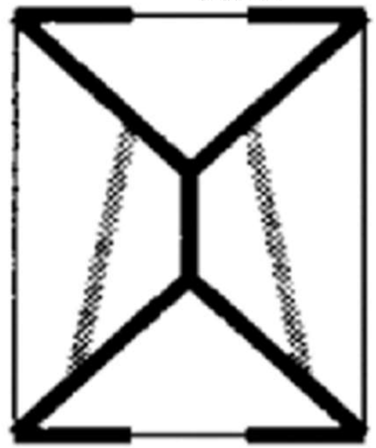
EMM



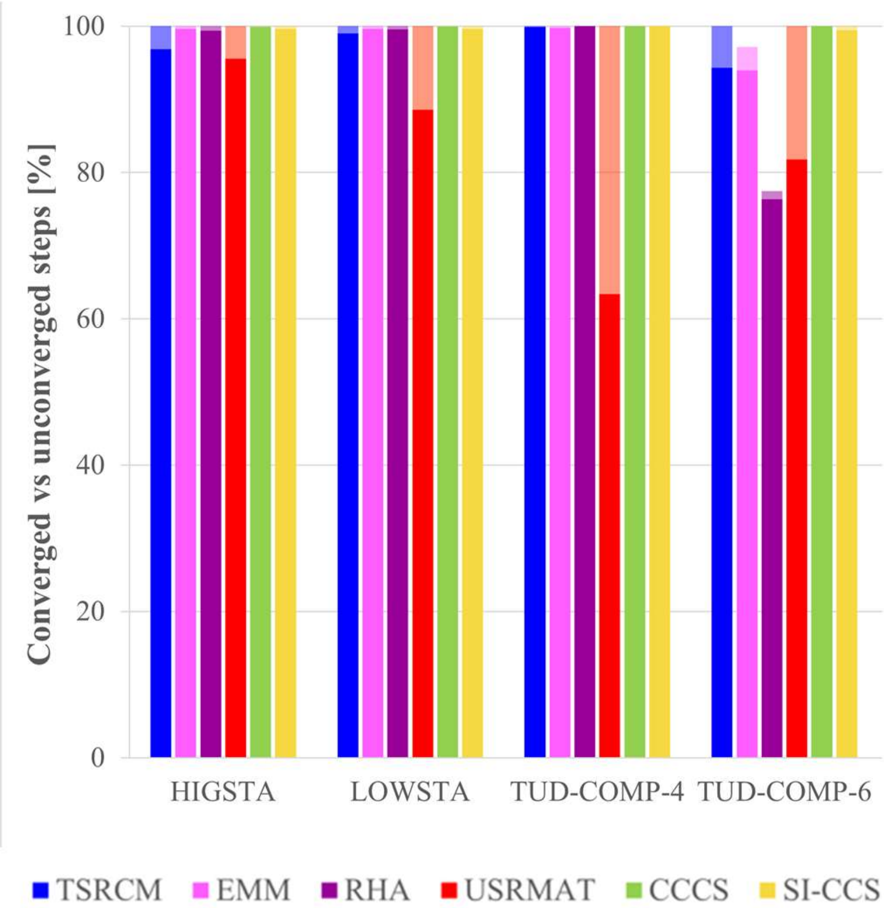
Rankine Hill Anisotropy







Computational time & effort



	TUD-COMP-4	TUD-COMP-6	LOWSTA	HIGSTA
TSRCM	0:17:49	1:31:34	0:06:48	0:18:07
EMM	0:11:44	-	0:03:12	0:04:17
RHA	0:45:54	-	1:01:35	1:14:54
USRMAT	1:12:53	1:16:27	0:19:20	0:12:25
CCCS	0:18:30	1:04:54	0:09:05	0:11:56
SI-CCS	0:37:37	1:40:26	0:16:15	0:23:18

TUDelft

Conclusions

- ❑Accurate prediction of base shear capacity
- ❑Improvement of dissipated energy
- ❑Sharp damage localization
- ❑Numerical instabilities
- ❑Computational time

Thank you ☺

TU Delft

Tensile Behaviour

Tensile strength

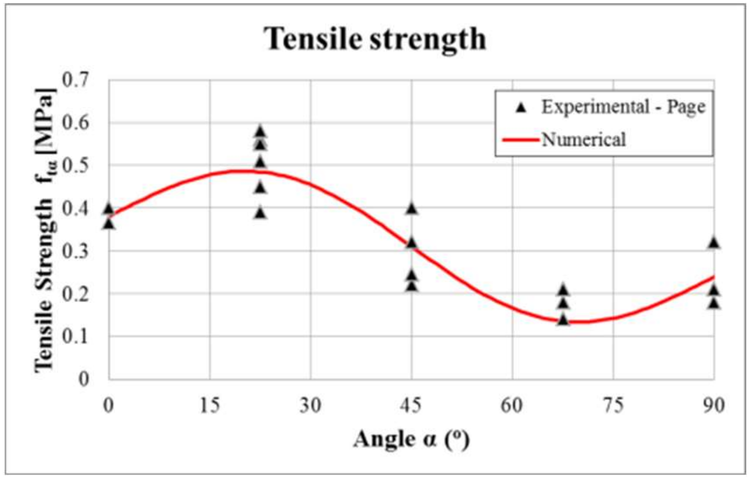
$$f_t(\theta) = f_{t0} - (f_{t0} - f_{t90}) \cdot \frac{|\theta|}{\frac{\pi}{2}} + \left(f_{tmax} - \frac{f_{t1} + f_{t2}}{2}\right) \cdot \sin(4\theta)$$

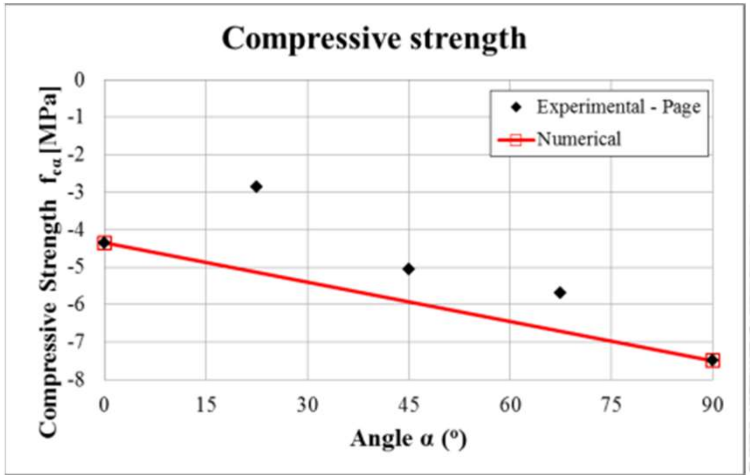
with $f_{tmax} = \sqrt{f_{t0}^2 + f_{t90}^2}$

Post-peak behaviour

$$\beta(\theta) = \begin{cases} \dfrac{\beta_0 (\theta - \theta_{fr})^2}{\theta_{fr}^2} & for\ \ 0 \leq \theta < \theta_{fr} \\ 0 & for\ \ \theta_{fr} \leq \theta < \pi/4 \\ \beta_{90} \sin\left(2\left(\theta_p - \dfrac{\pi}{4}\right)\right) & for\ \theta > \pi/4 \end{cases}$$

$$\& \ \bar{\varepsilon}_{ult}(\theta) = \begin{cases} \dfrac{1}{\beta(\theta)} + 1 & for\ \ 0 \leq \theta < \theta_{fr} \\ 100 \cdot \bar{\varepsilon}_{ul,90} & for\ \ \theta_{fr} \leq \theta < \pi/4 \\ \dfrac{1}{\beta(\theta)} + 1 & for\ \theta > \pi/4 \end{cases}$$





Compressive Behaviour

$$f_c(\theta) = f_{c0} + (f_{c90} - f_{c0}) \cdot \frac{|\theta|}{\frac{\pi}{2}}$$

$$G_{fc}(\theta) = \alpha_c + (G_{fc0} - G_{fc90}) \frac{|f_c(\theta)|}{|f_{c0}| - |f_{c90}|}$$

with $\alpha_c = \dfrac{(G_{fc90} \cdot |f_{c0}| - G_{fc0} \cdot |f_{c90}|)}{|f_{c0} - f_{c90}|}$