Application of fracture mechanics for settlement damage prediction

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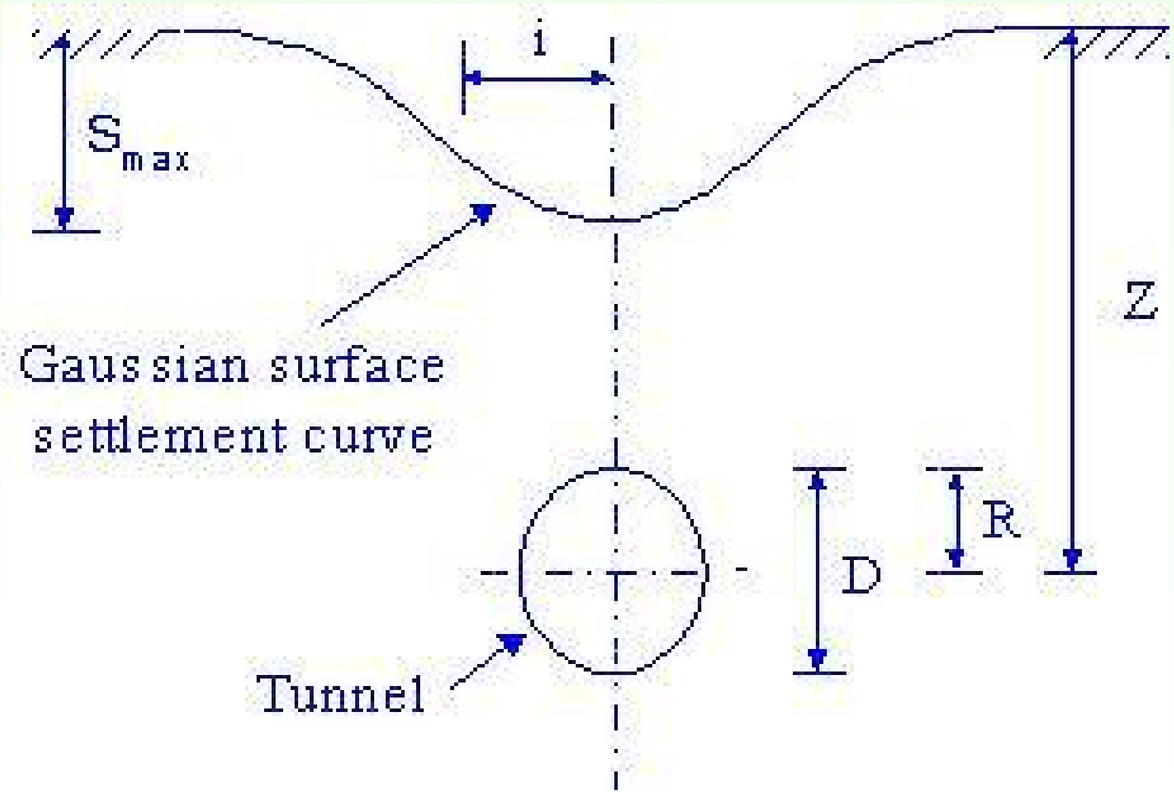
Outline

- Background and motivation
- Semi-coupled analysis (2D Example)
- Large-scale continuum and discrete crack analyses
- Coupled analysis

Background: Induced settlement by bored tunnelling

The bored tunnelling activities lead to surface settlements that may damage neighbouring structures, especially the historical masonry buildings.



The greenfield surface settlement caused by bored tunnelling

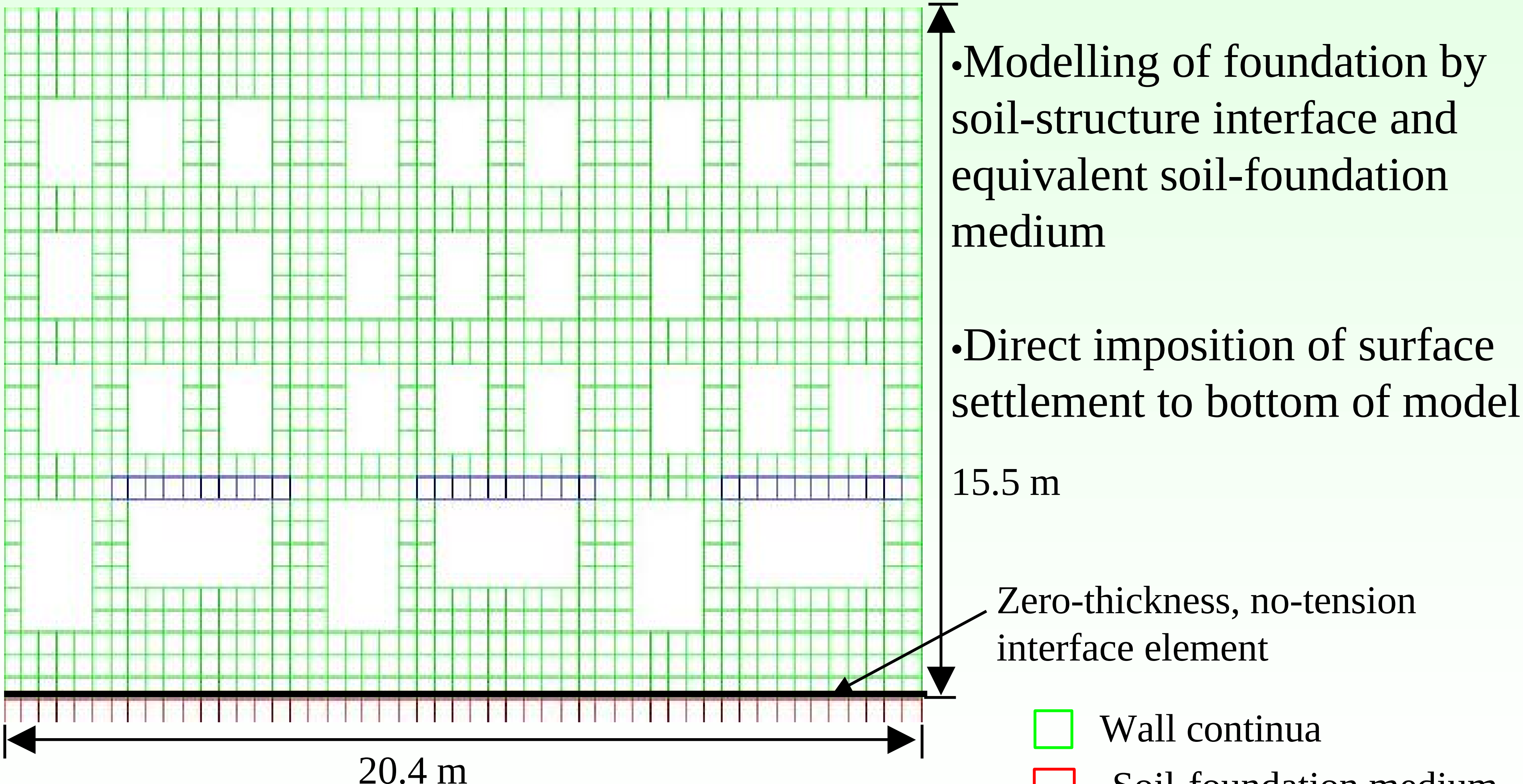
Motivations

- Lack of the reliable either analytical or empirical method for evaluating the cracking damage of above ground structures

- Limitation of current analytical and empirical methods to provide the reliable information for making engineering decision in this coupled interaction analysis

- Significant need of the robust and versatile numerical model for this class of soil-structure interaction problem

Semi-coupled analysis

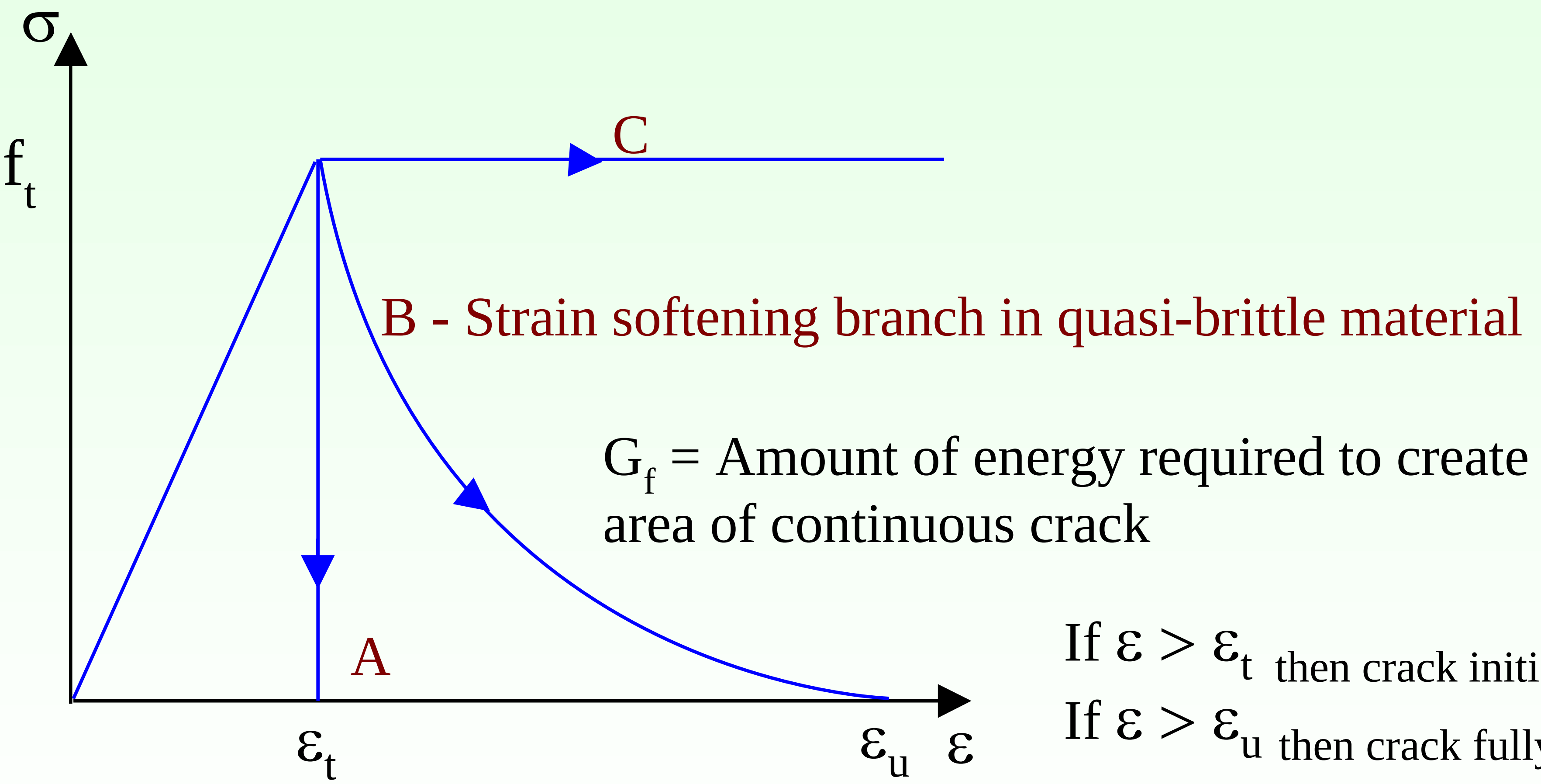


Mesh layout in semi-coupled analysis

- Modelling of foundation by soil-structure interface and equivalent soil-foundation medium

- Direct imposition of surface settlement to bottom of model

Nature of quasi-brittle material



G_f = Amount of energy required to create one unit of area of continuous crack

If $\varepsilon > \varepsilon_t$ then crack initiates

If $\varepsilon > \varepsilon_u$ then crack fully opens

A - Brittle material e.g. Glass

B - Quasi-brittle material e.g. Masonry, Concrete

C - Plastic material e.g. Steel

Material properties

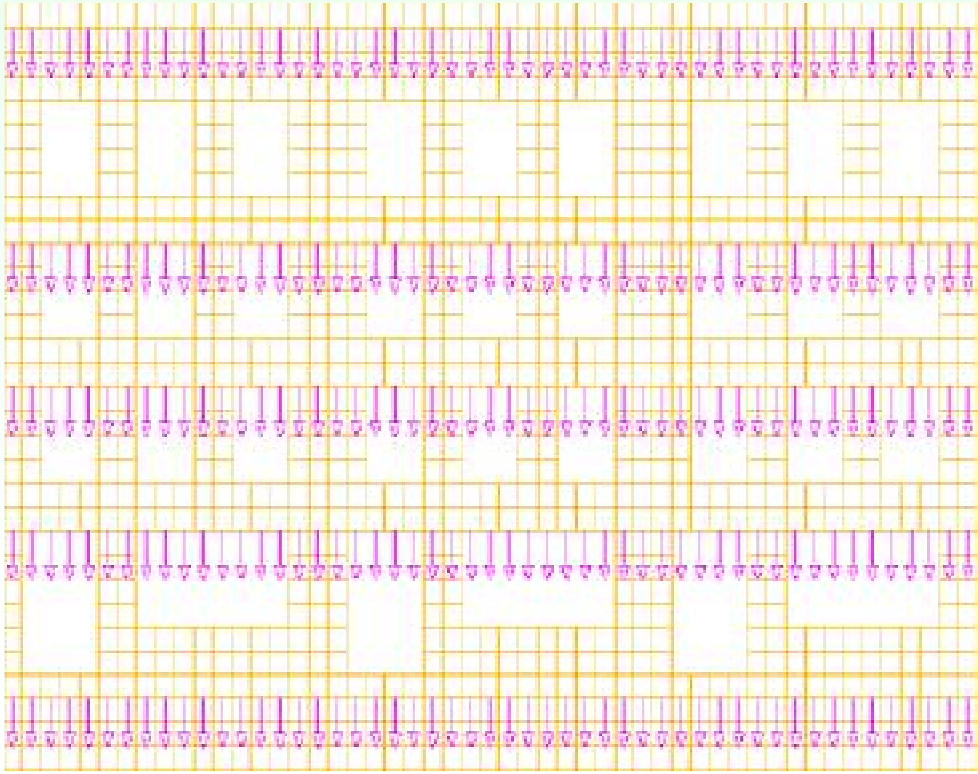
Masonry, decomposed strain fixed smeared crack model by Rots (1988)

$E=6000\ N/mm^2$, $\nu=0.2$, $f_t=0.3 N/mm^2$, $G_f = 0.05 N/mm$

No-tension bedding interface, $K=0.15\ N/mm^3$

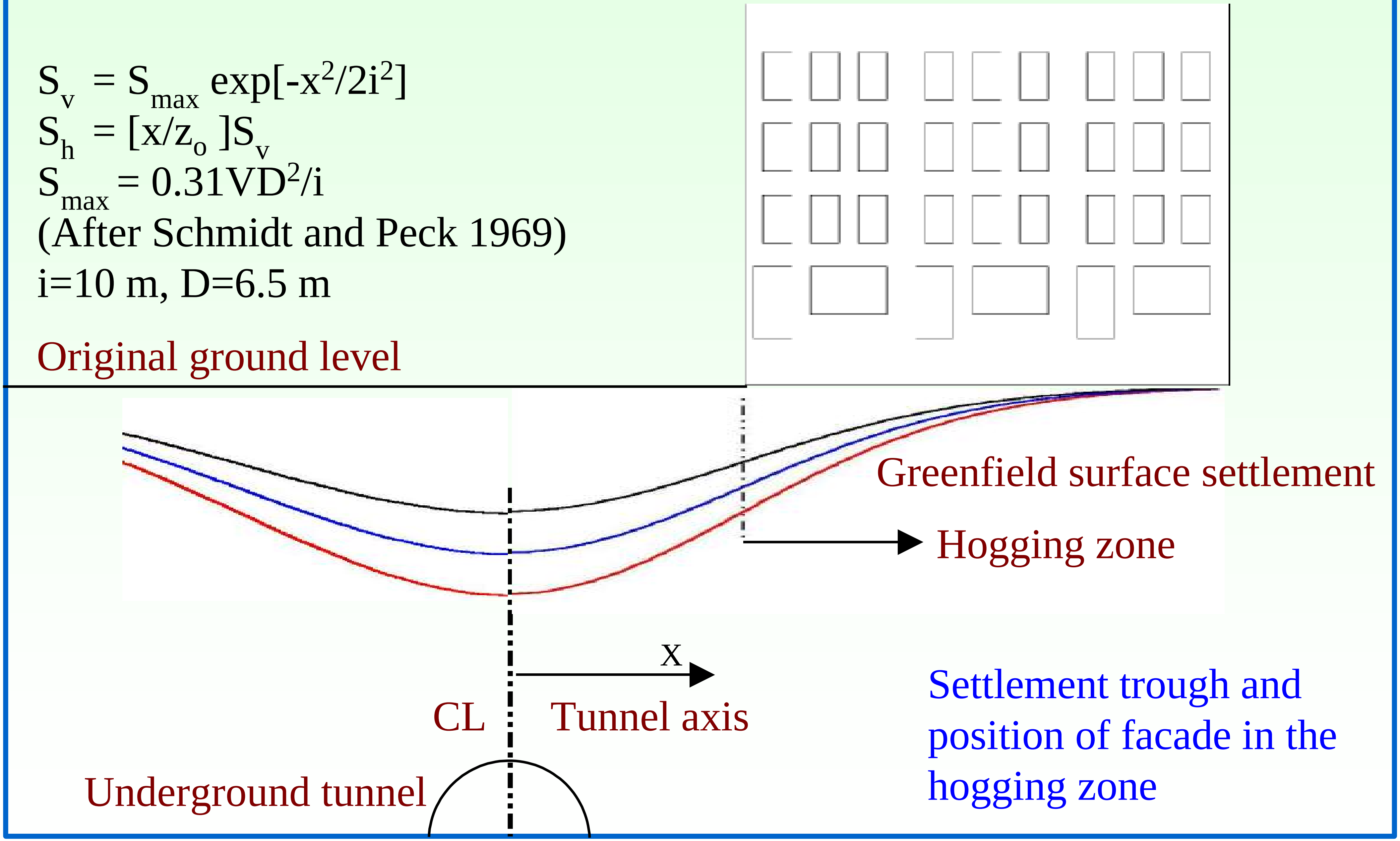
Loading scheme

1) Self weight
2) Live load at each floor = 5 kN/m
3) Prescribed displacement loading of surface settlement

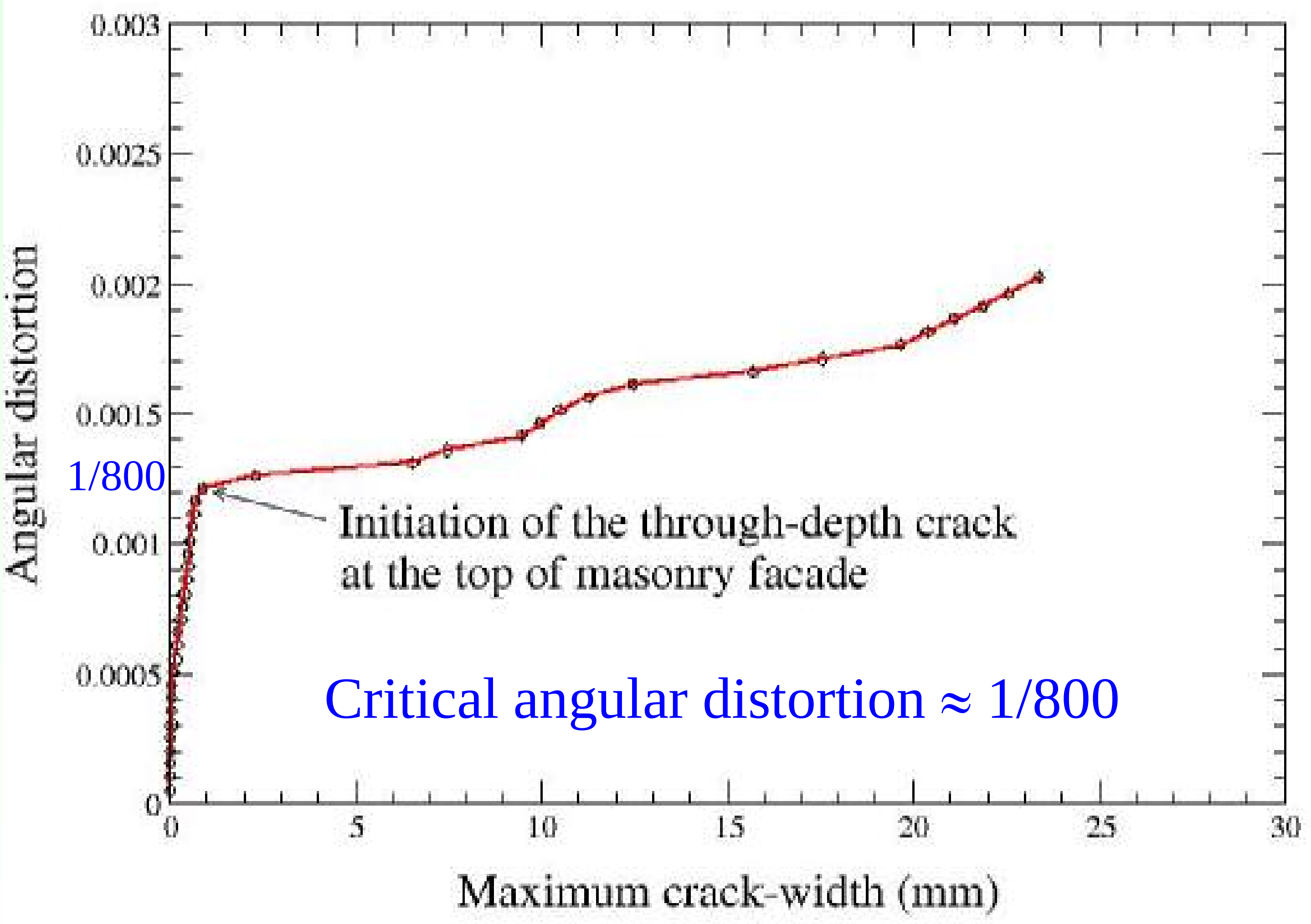


Induced surface settlement

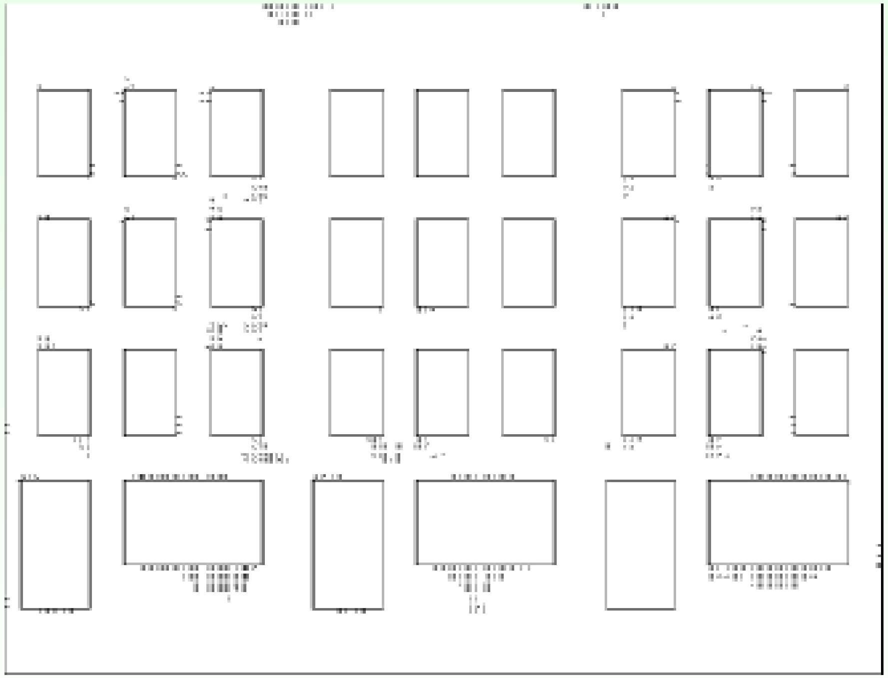
$S_v = S_{max} \exp[-x^2/2i^2]$
$S_h = [x/z_o]S_v$
$S_{max} = 0.31VD^2/i$
(After Schmidt and Peck 1969)
i=10 m, D=6.5 m



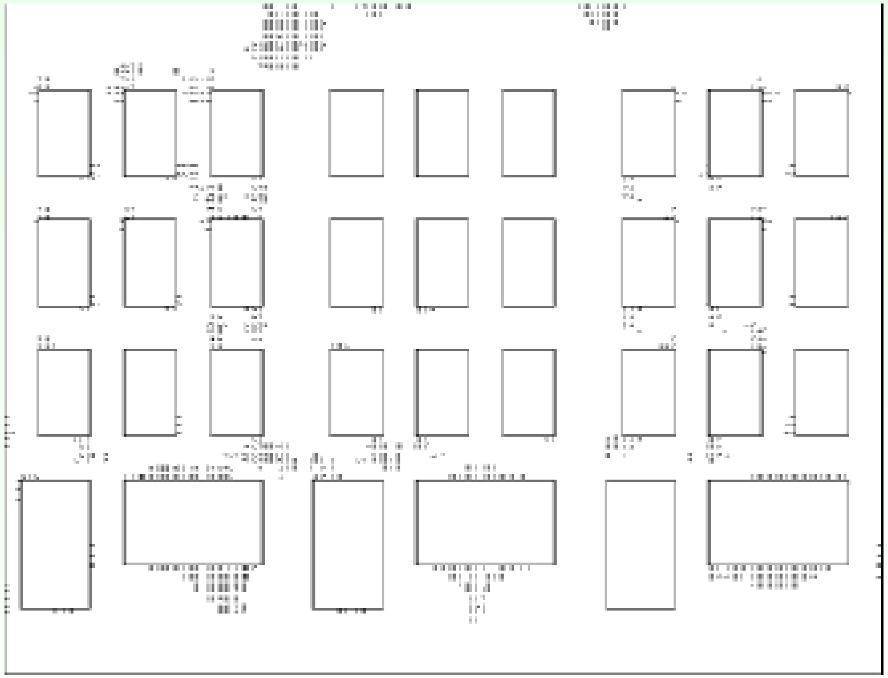
Settlement trough and position of facade in the hogging zone



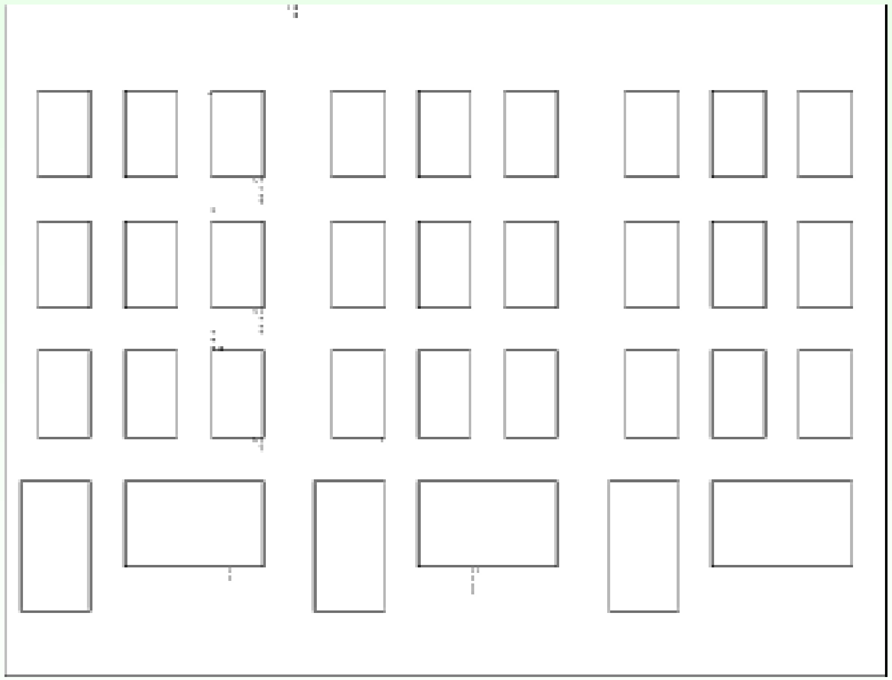
Relation between angular distortion and maximum crack-width



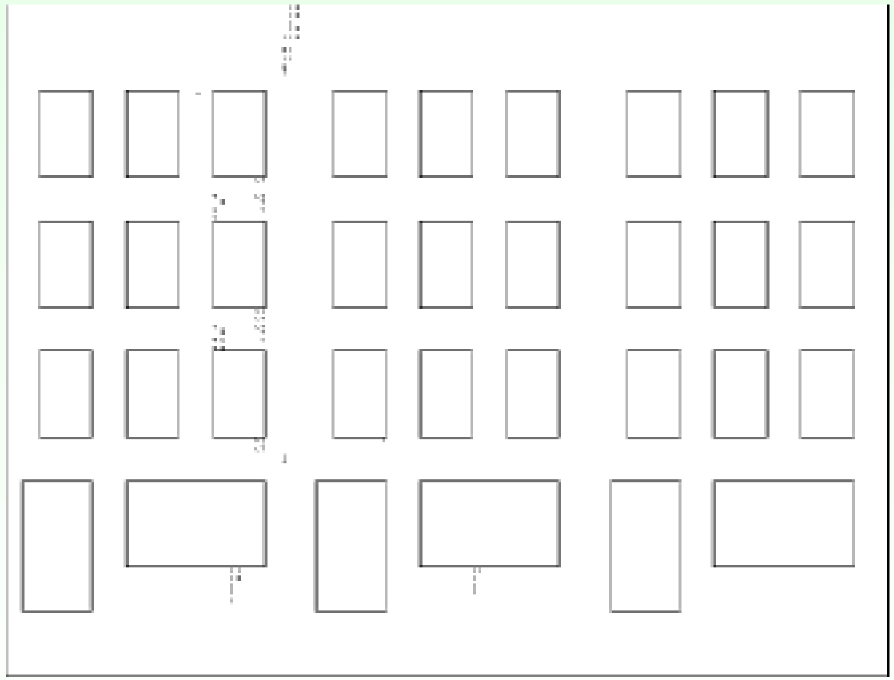
Crack pattern at angular distortion = 1/1000



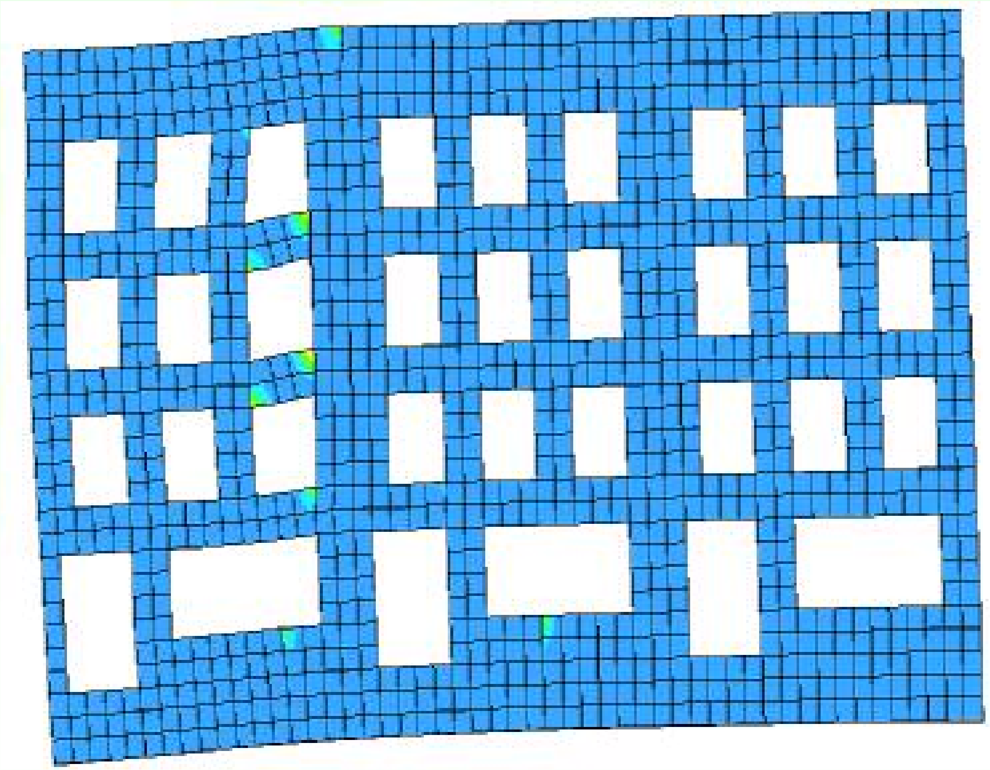
Crack pattern at critical angular distortion = 1/800



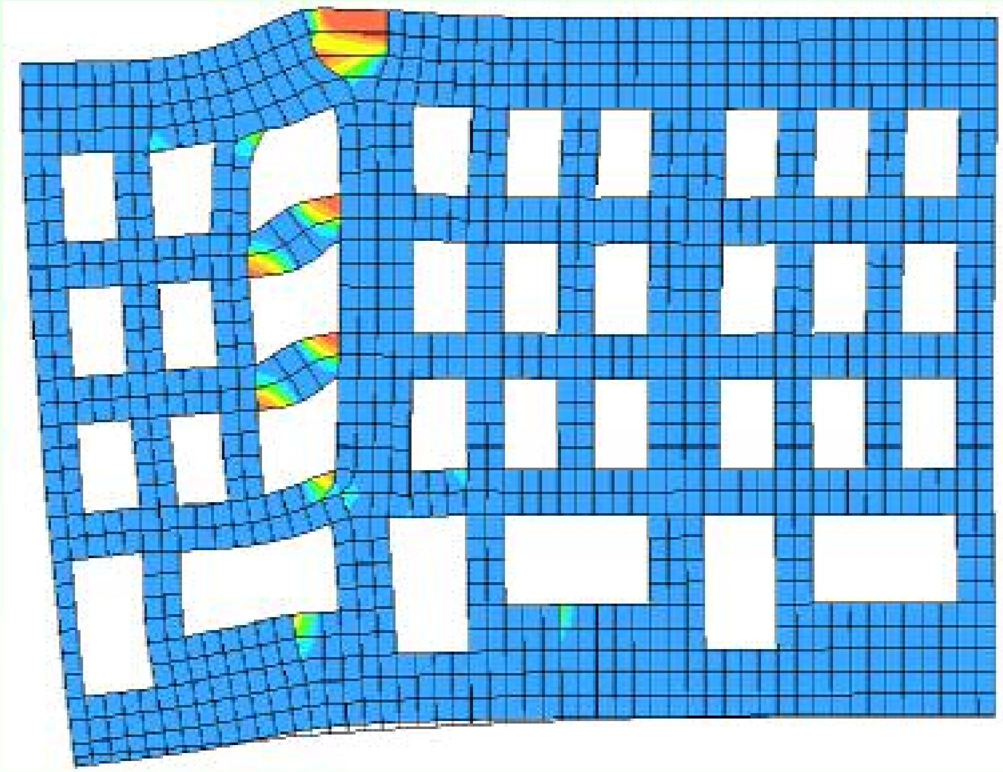
Fully-open crack at critical angular distortion



Fully-open crack after critical angular distortion



Deformed mesh and principal strain at critical angular distortion



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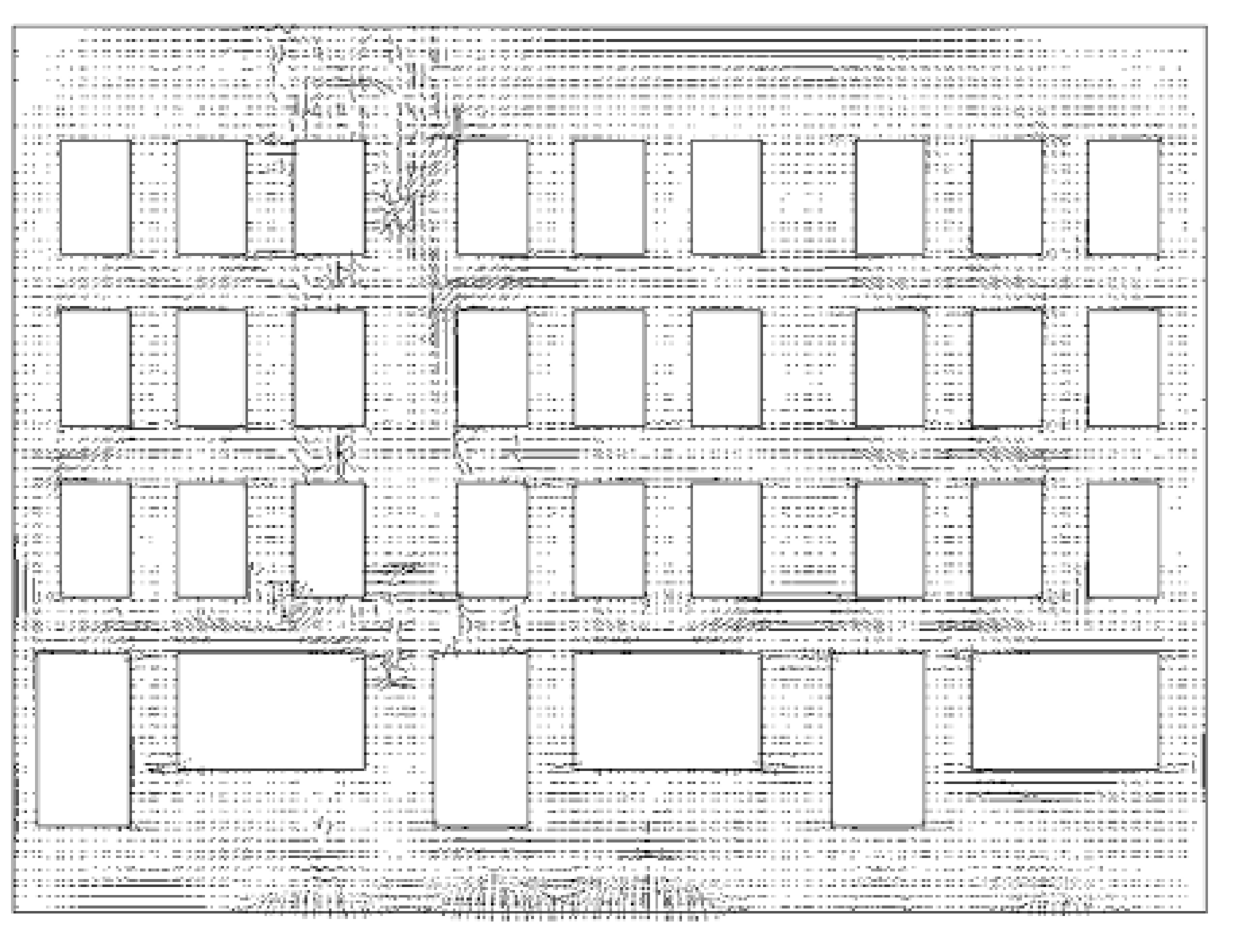
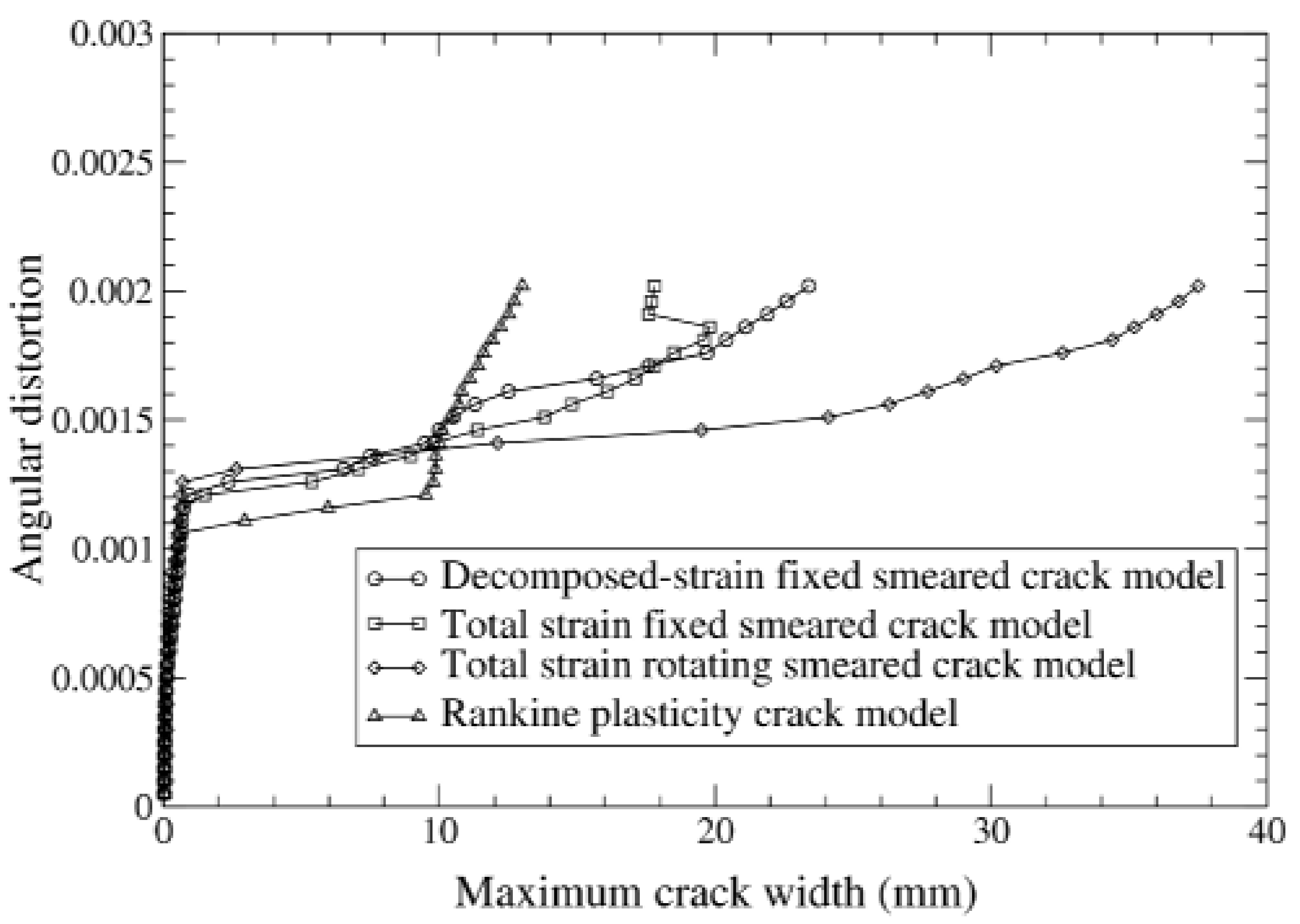
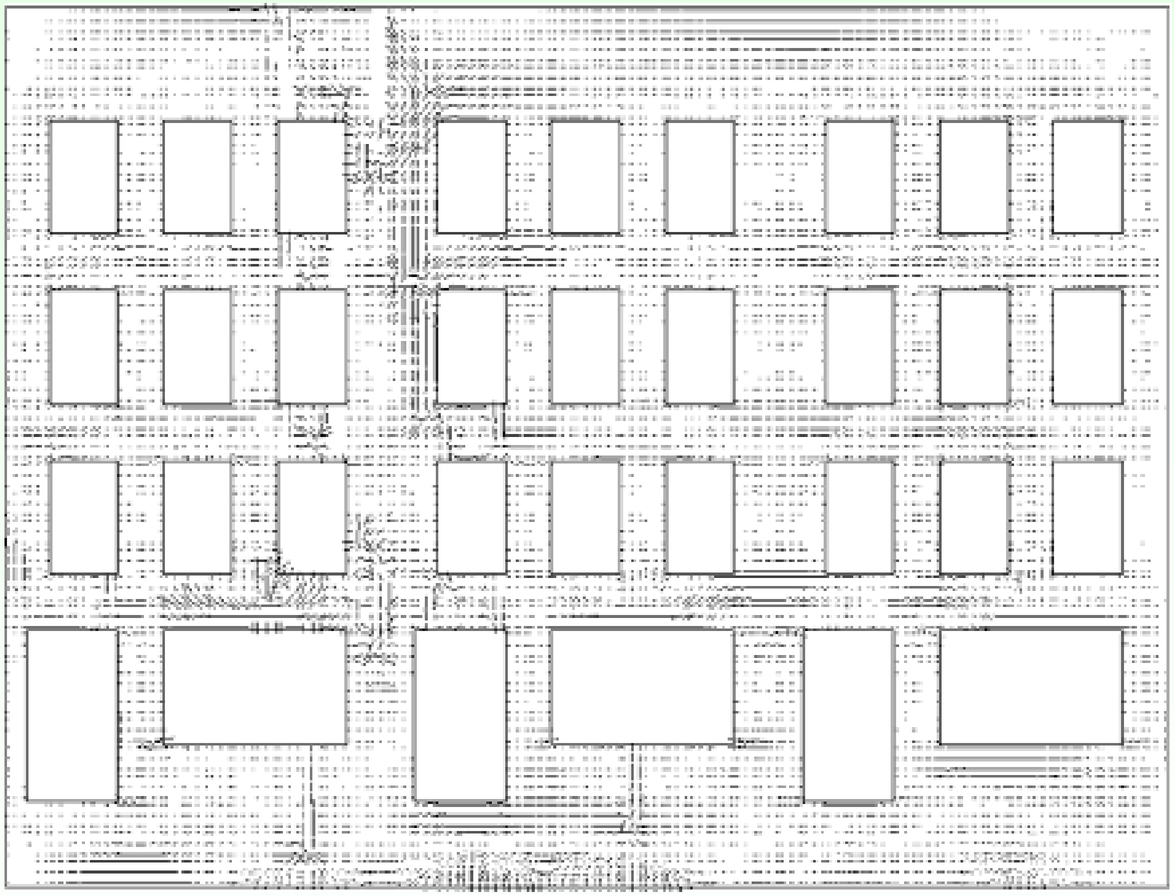


Stress locking after the critical angular distortion

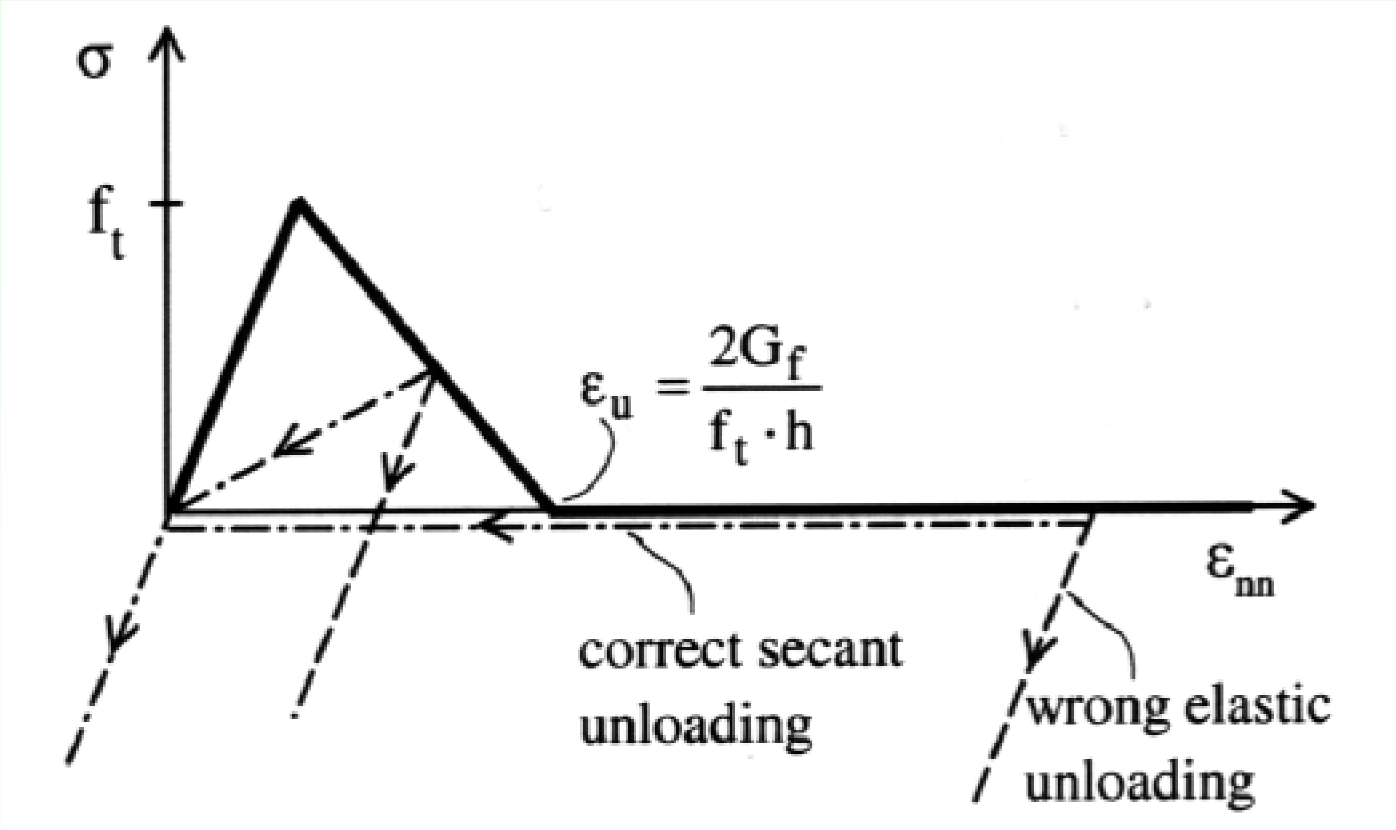
Performance of continuum crack models in large-scale fracture



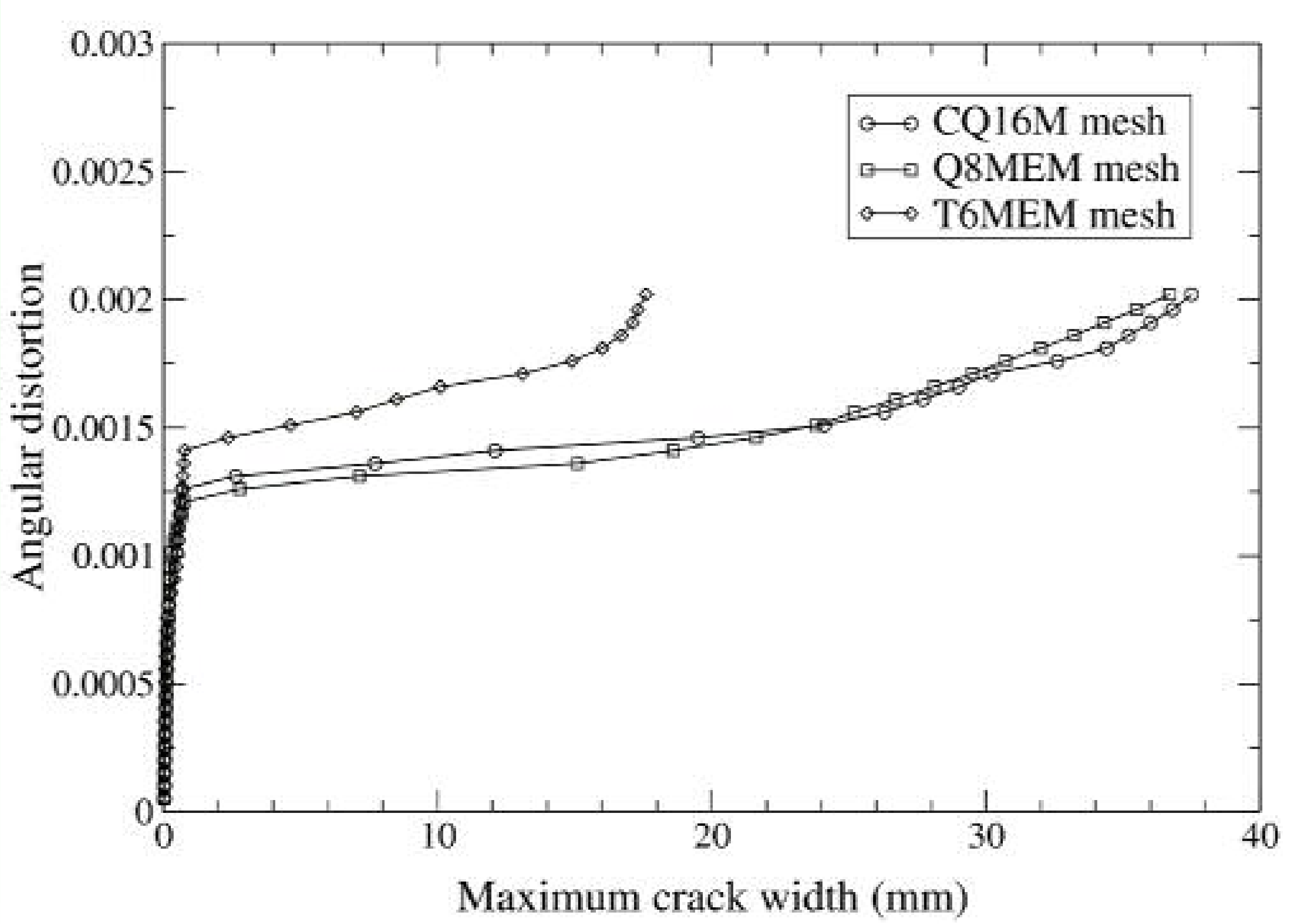
- Two-stage mechanism of cracking response
- Convergence problem in the second plateau

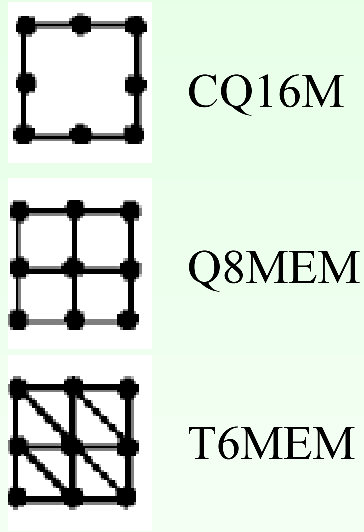


Reduction of stress locking zone by total strain rotating smeared crack model



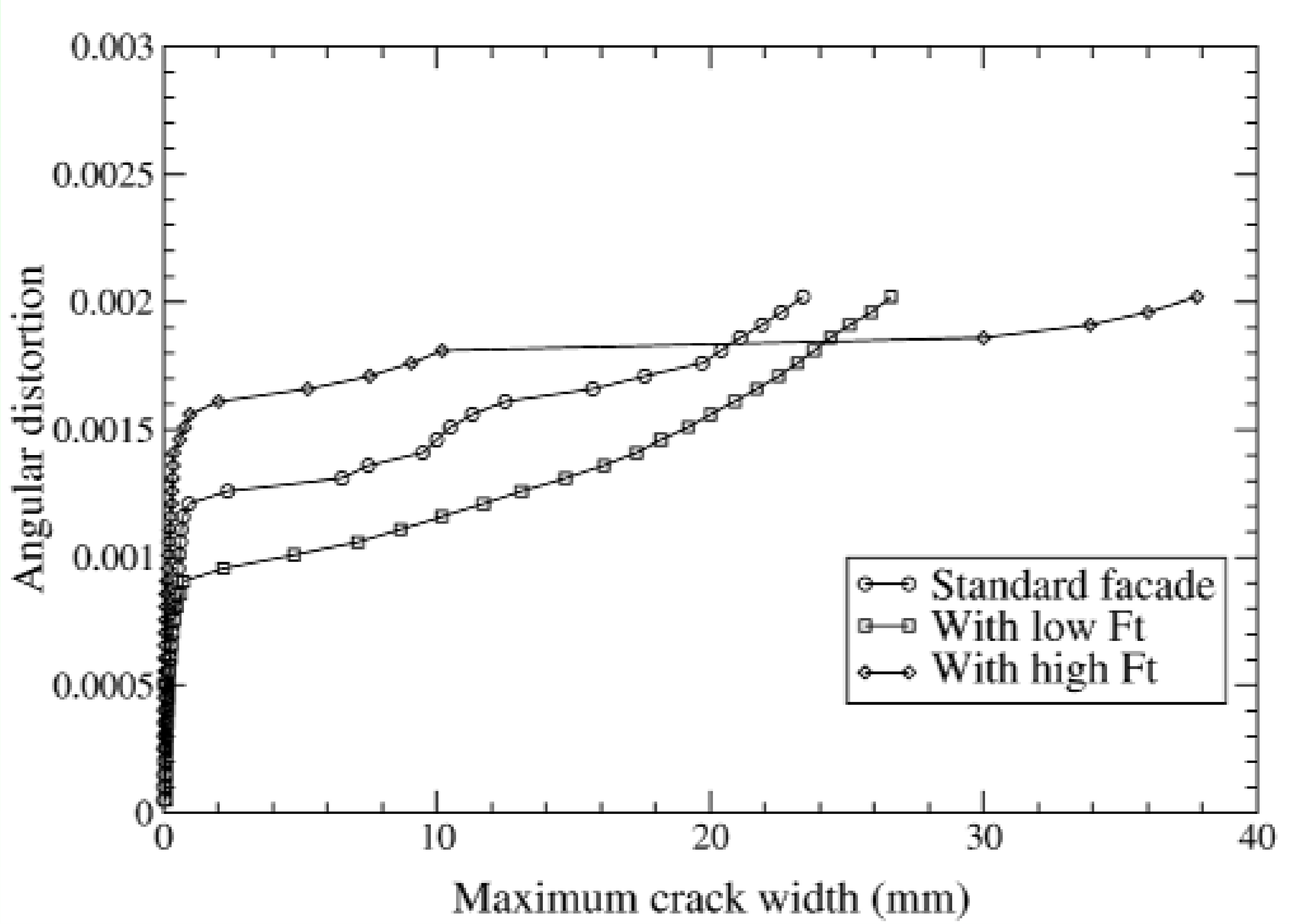
Improper unloading options in plasticity-based crack model in handling non-proportional loadings

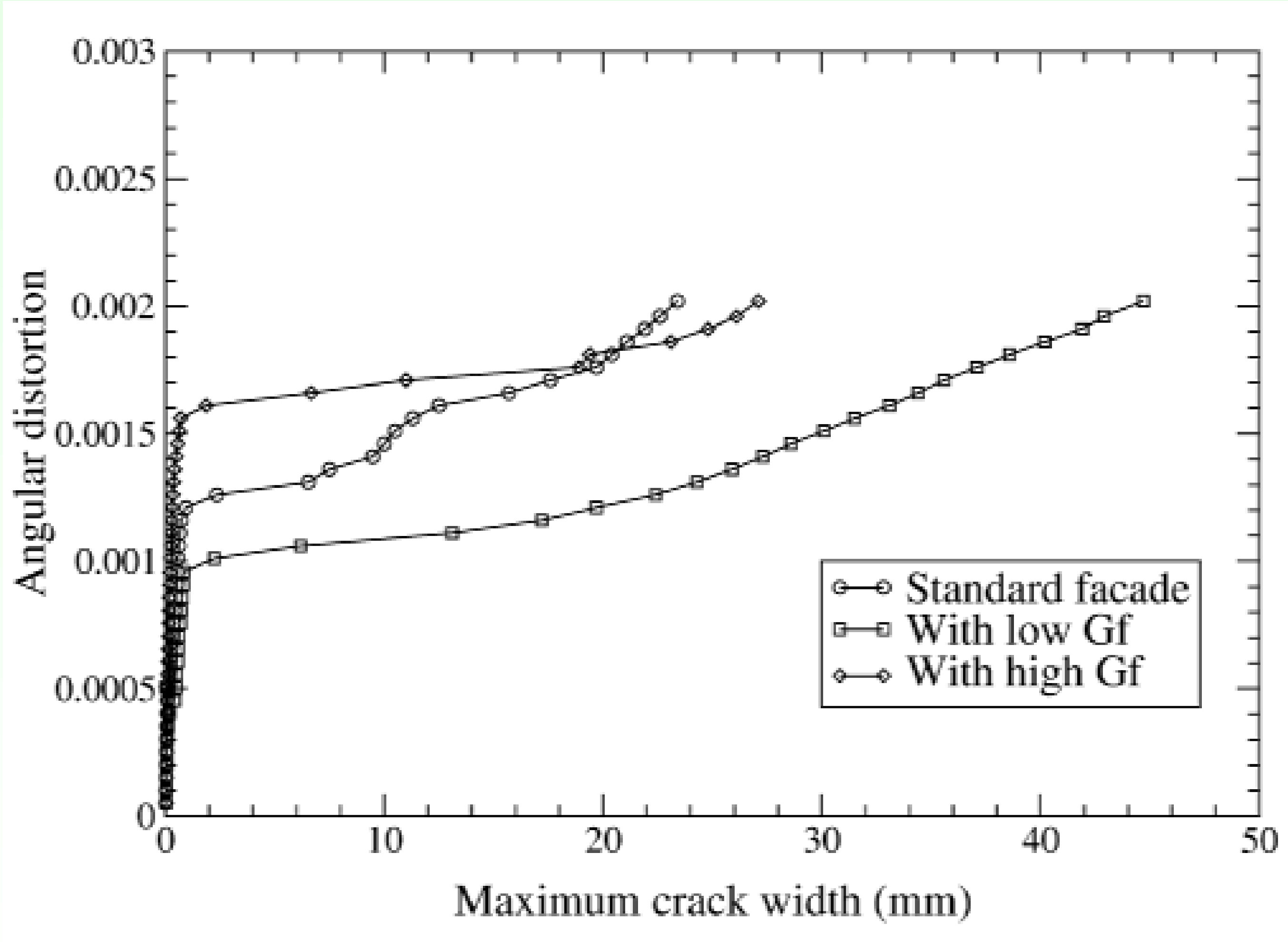




Mesh refinement test

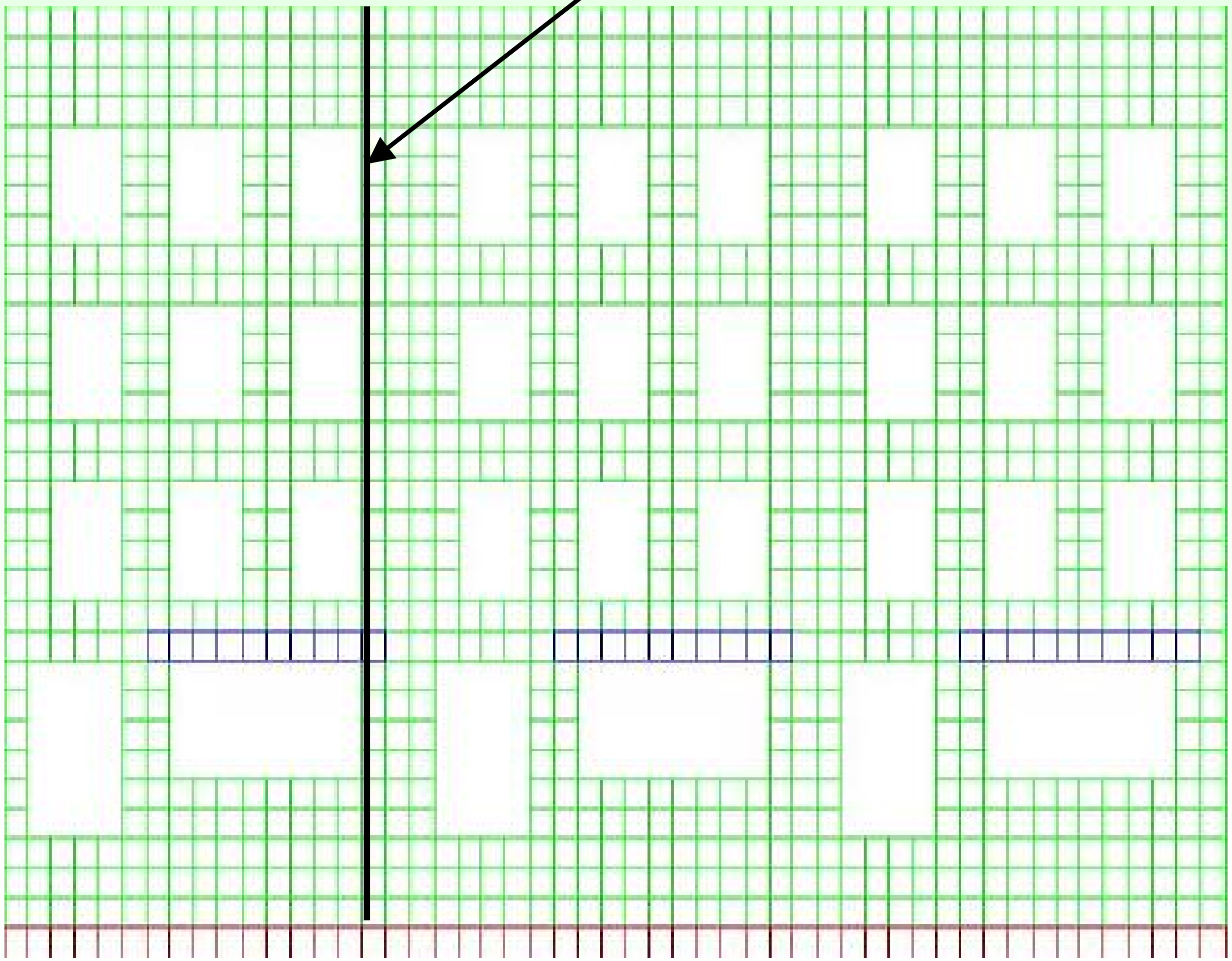
Effect of fracture properties on the building performance



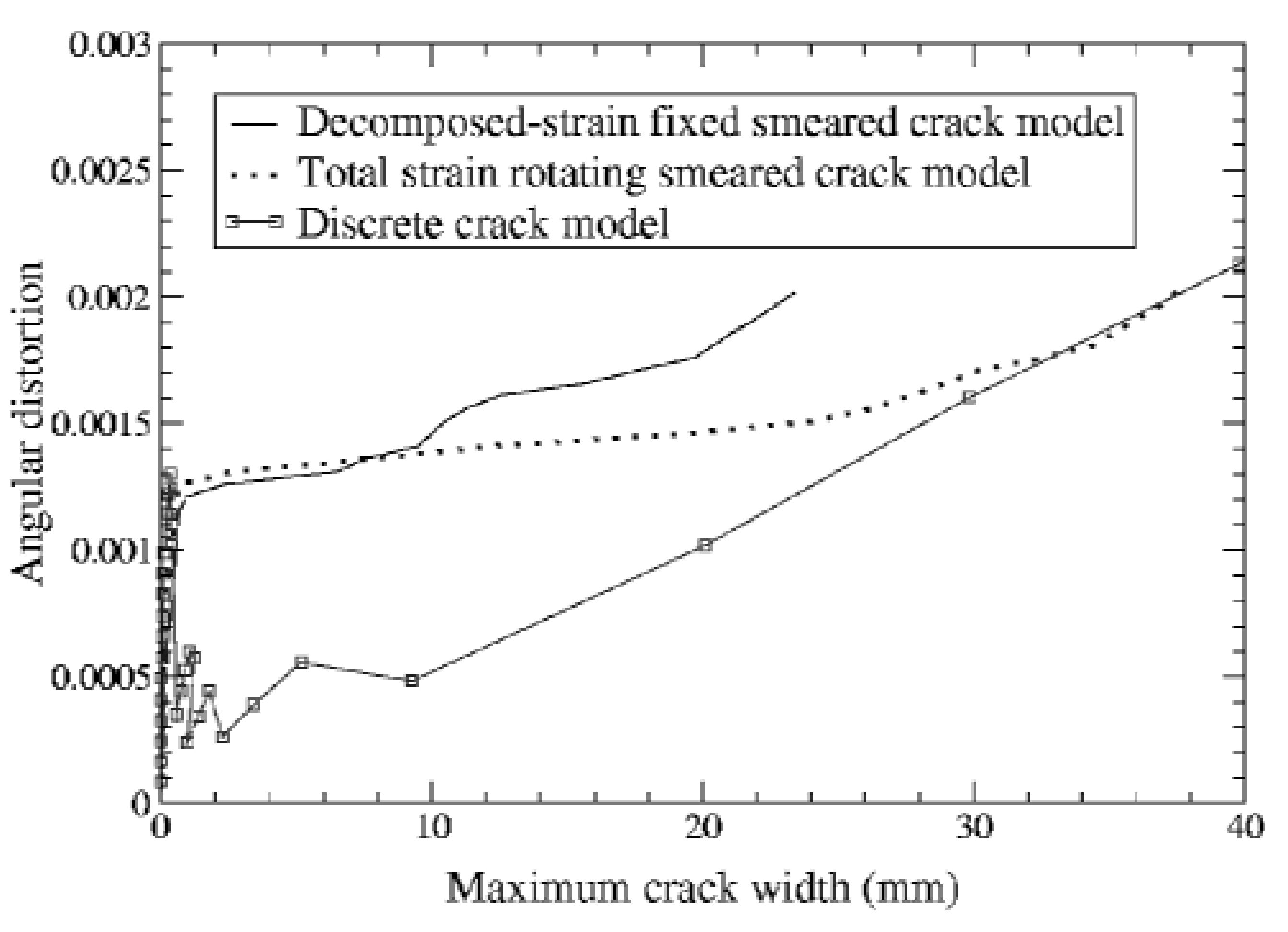


Angular distortion
Maximum crack width (mm)
Standard facade
With low Gf
With high Gf

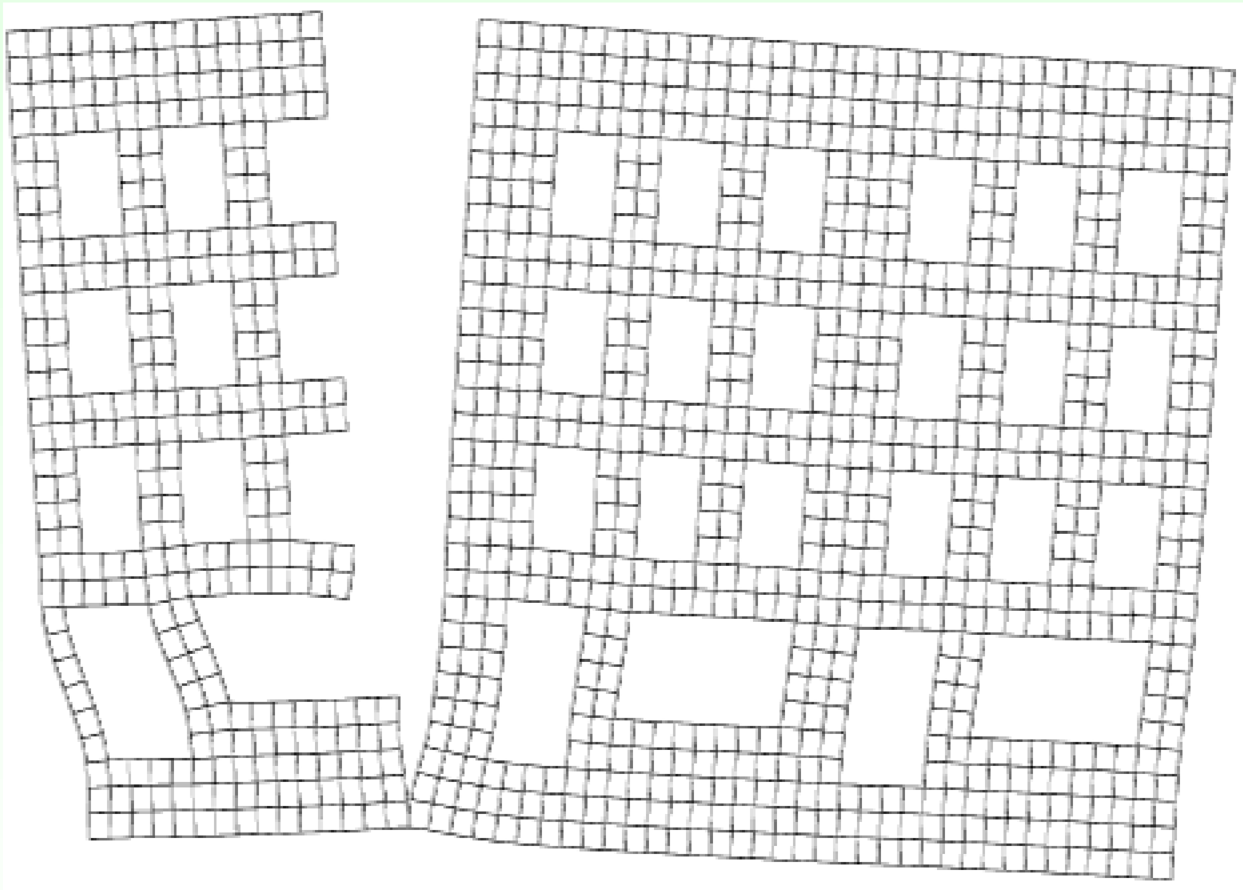
Discrete crack analysis



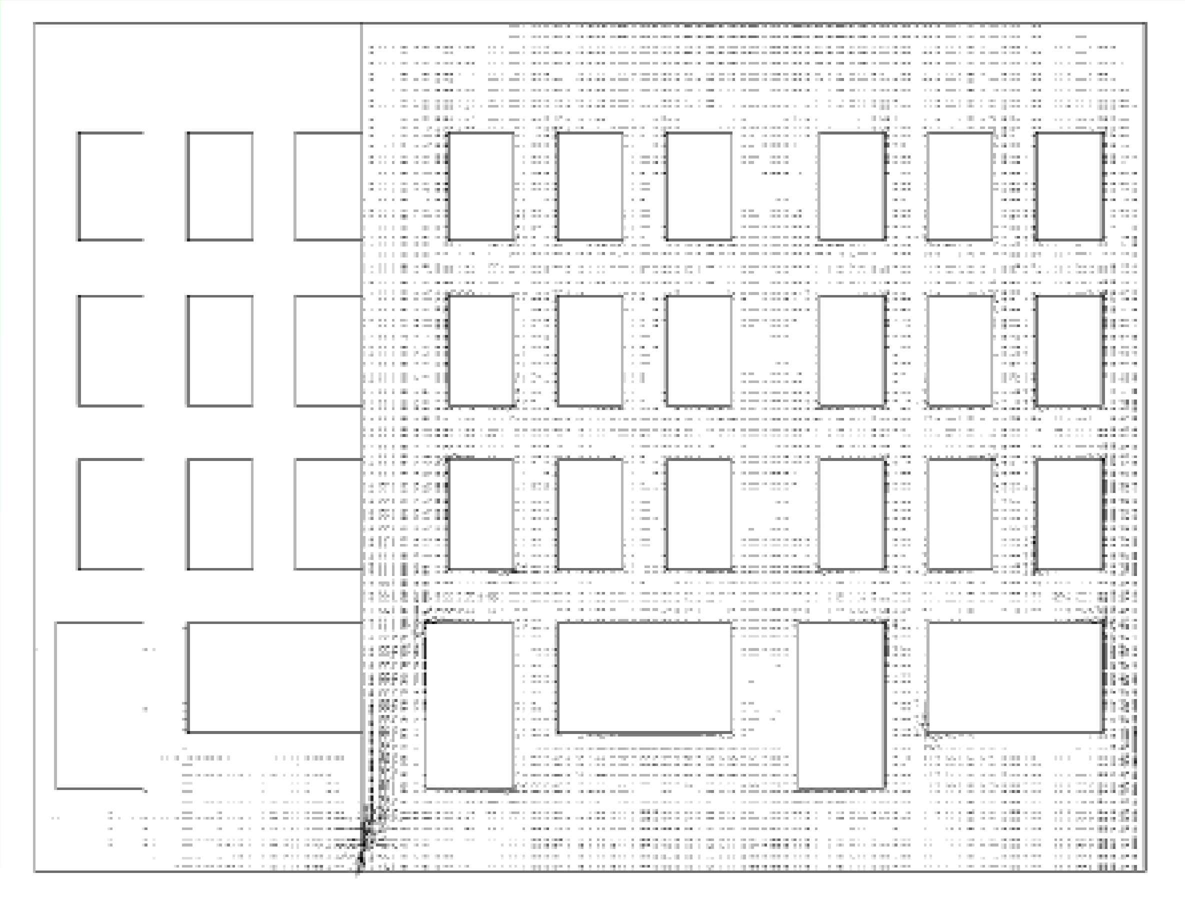
- Steer non-linear analysis by arc-length control technique
- Snap-back response due to significant difference between elastic stored energy and fracture energy



Computed angular distortion versus maximum crack width for the discrete crack analysis, compared with those by smeared crack analysis



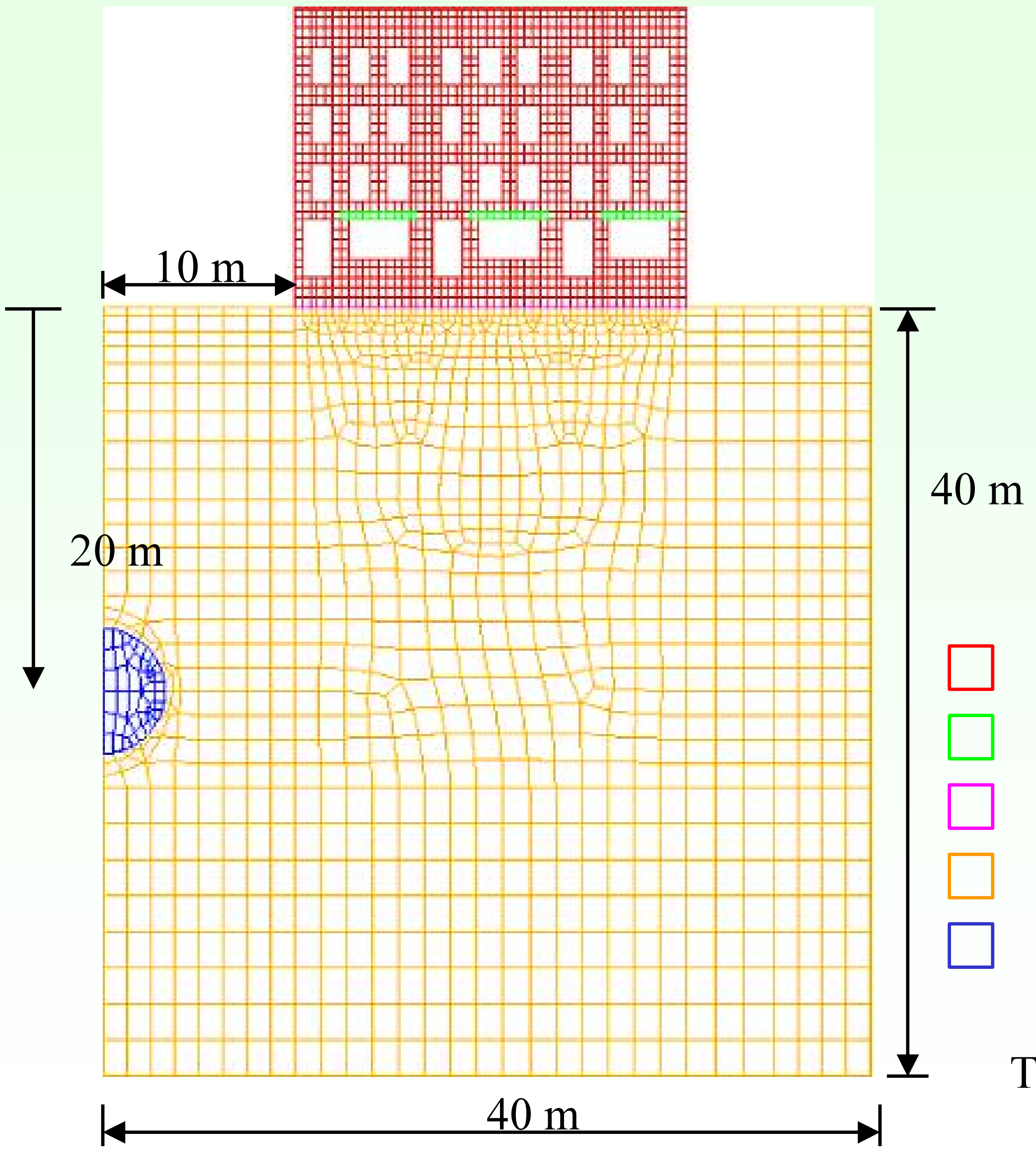
Incremental deformation during snap back response in discrete crack analysis



Residual principal tensile stress in discrete crack analysis

Coupled analysis

Allow for full interaction between underlying soil and masonry façade



- Masonry continuum
- Lintel
- Bedding interface
- Soil continuum
- Excavated soil

Tunnel diameter =6.5 m

Material properties

Masonry

$E=6000\ N/mm^2$, $\nu=0.2$, $f_t=0.3N/mm^2$, $G_f = 0.05N/mm$

No-tension bedding interface

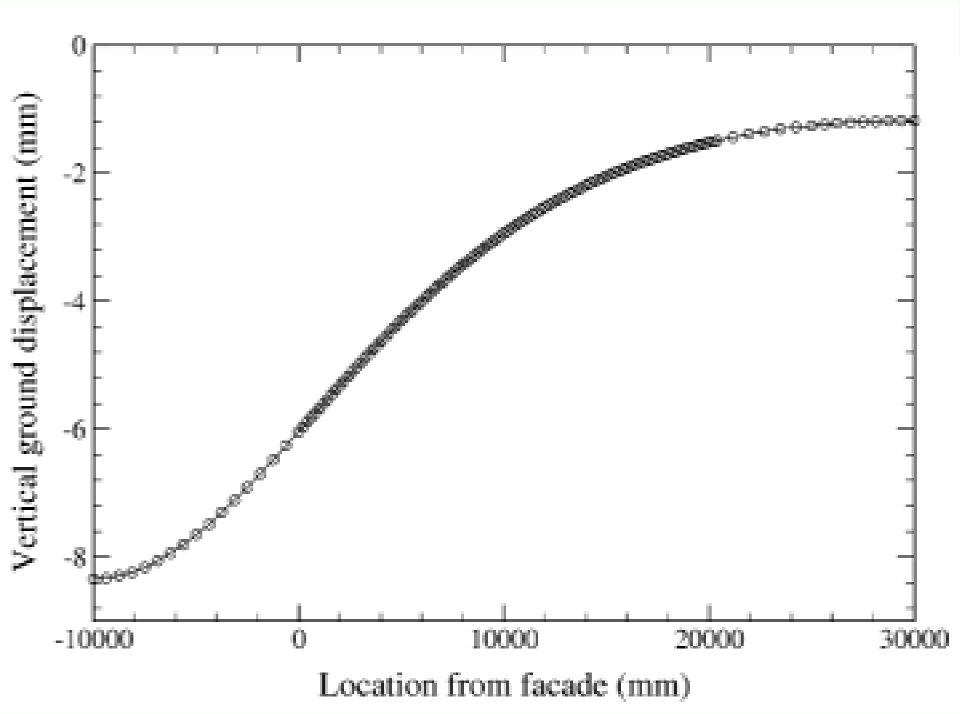
Soil

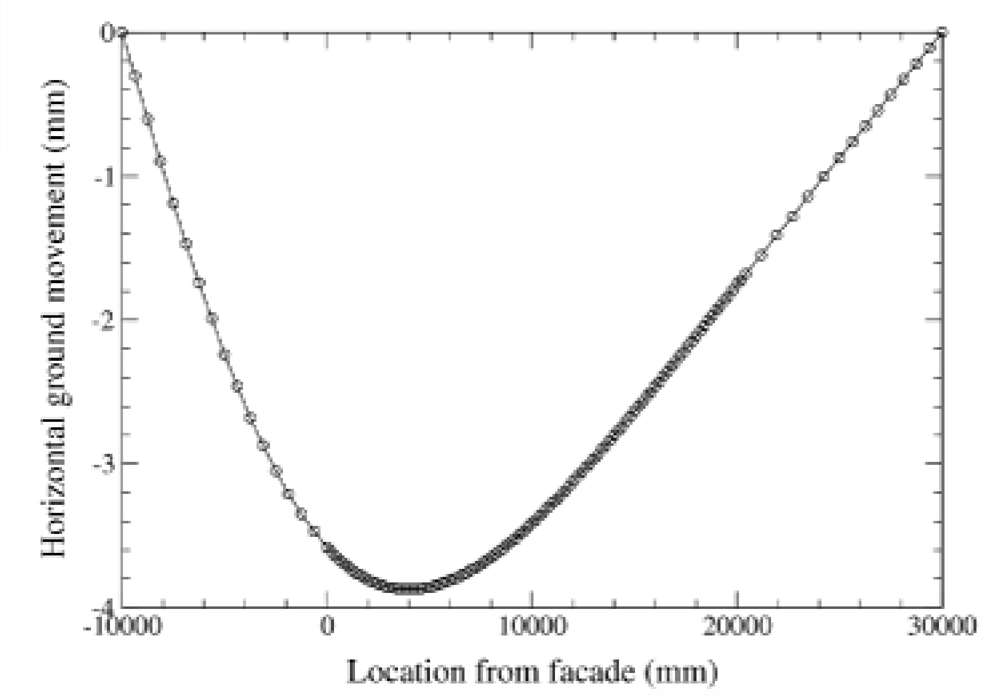
Basic soil model with three simplified strata

Depth	E (MPa)	ν	K_o	γ (kN/m^3)
0-10 m	10	0.35	0.748	17
10-25 m	30	0.35	0.748	17
25-40 m	100	0.30	0.357	20

Excavation simulation

Realistic inverted Gaussian settlement curve predicted for greenfield situation

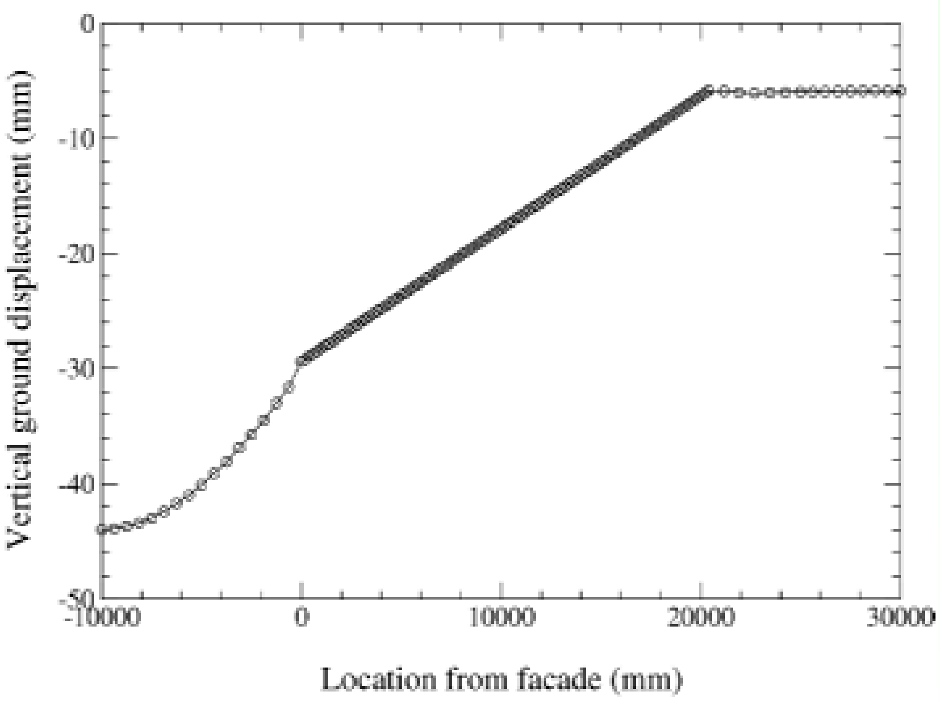


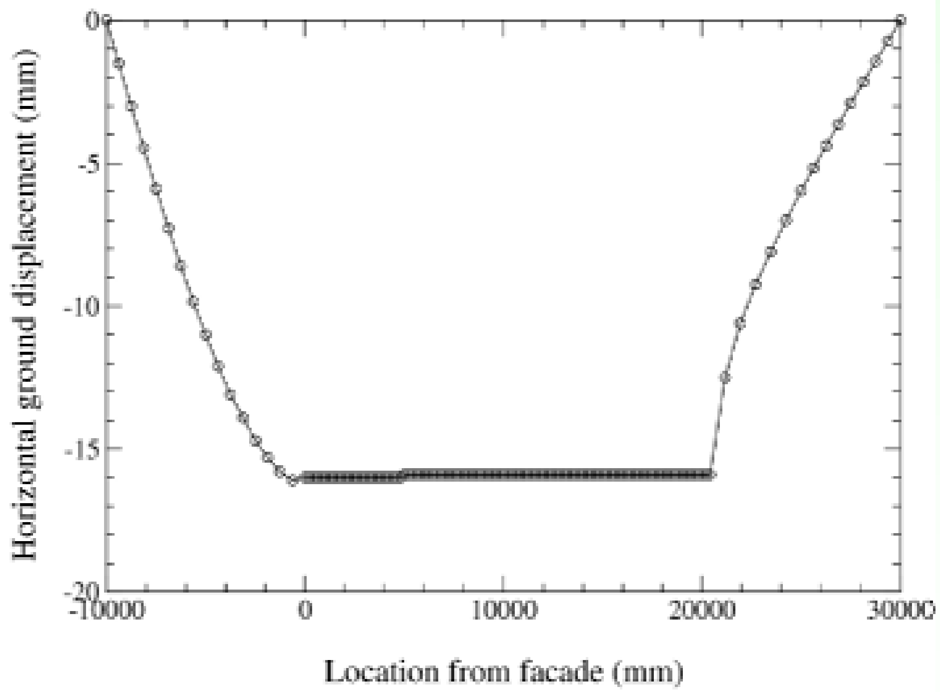


Greenfield movement profile at volume loss = 1%

For a façade with sufficient fracture strength

Observed negligible cracking damage but functionally undesirable tilt and building movement in range of 1-5 % volume loss

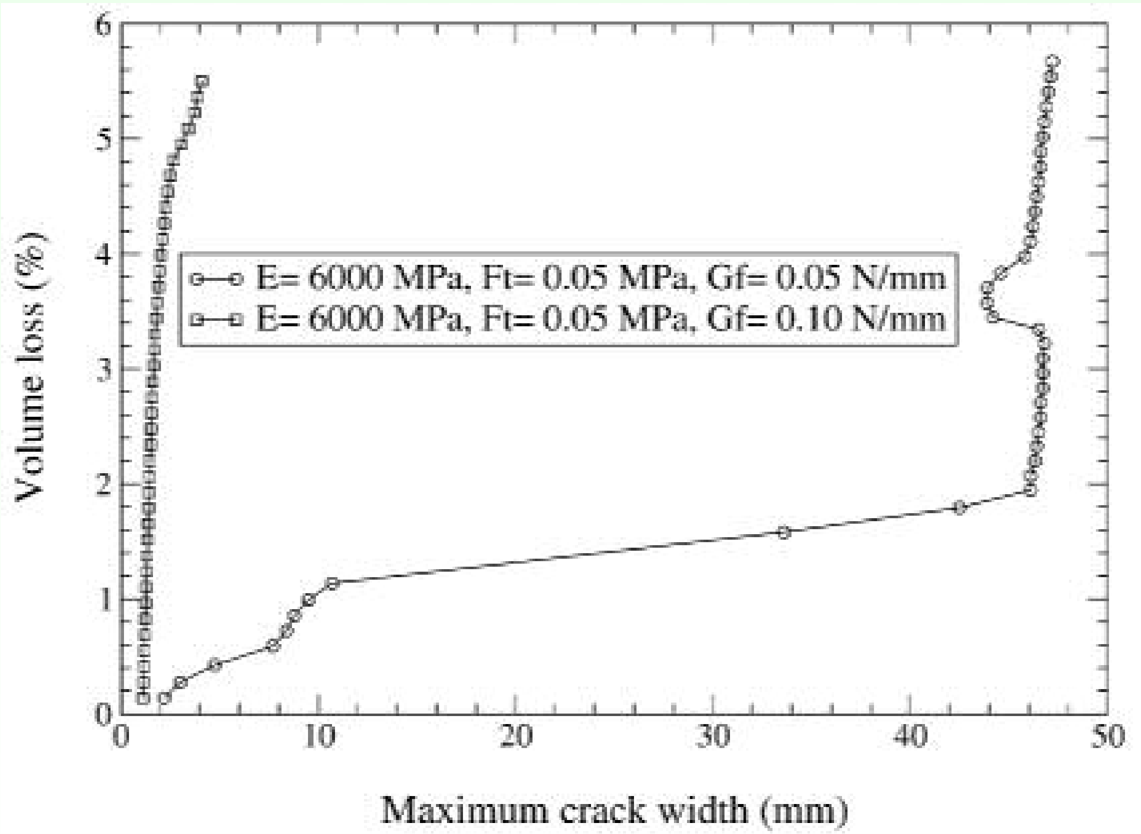




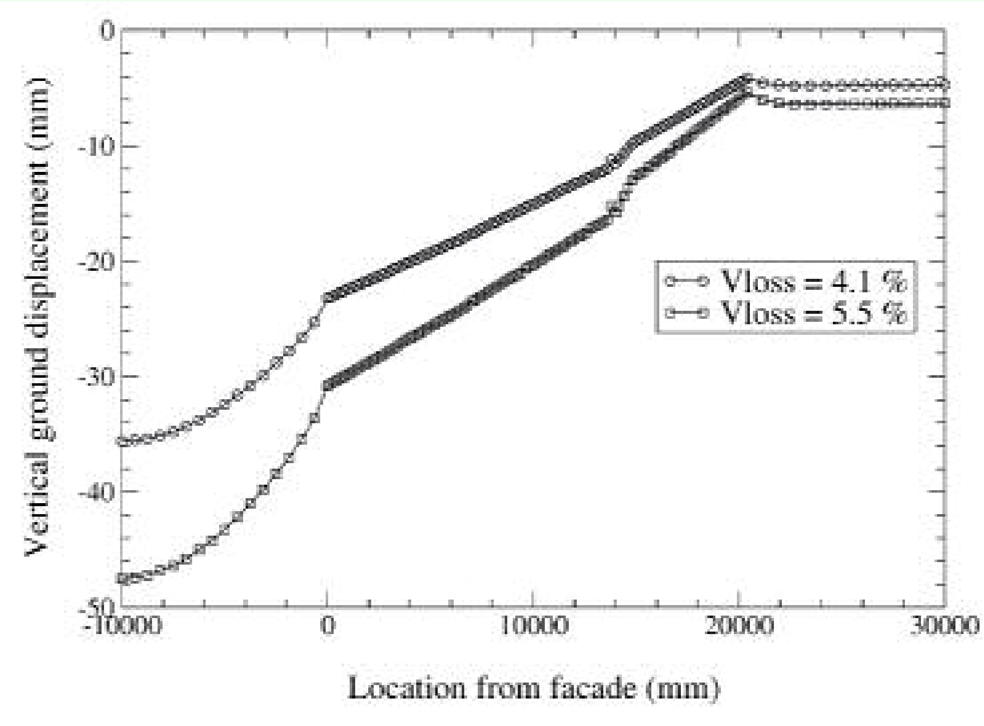
Influence of building stiffness on ground movement profile at volume loss = 5%

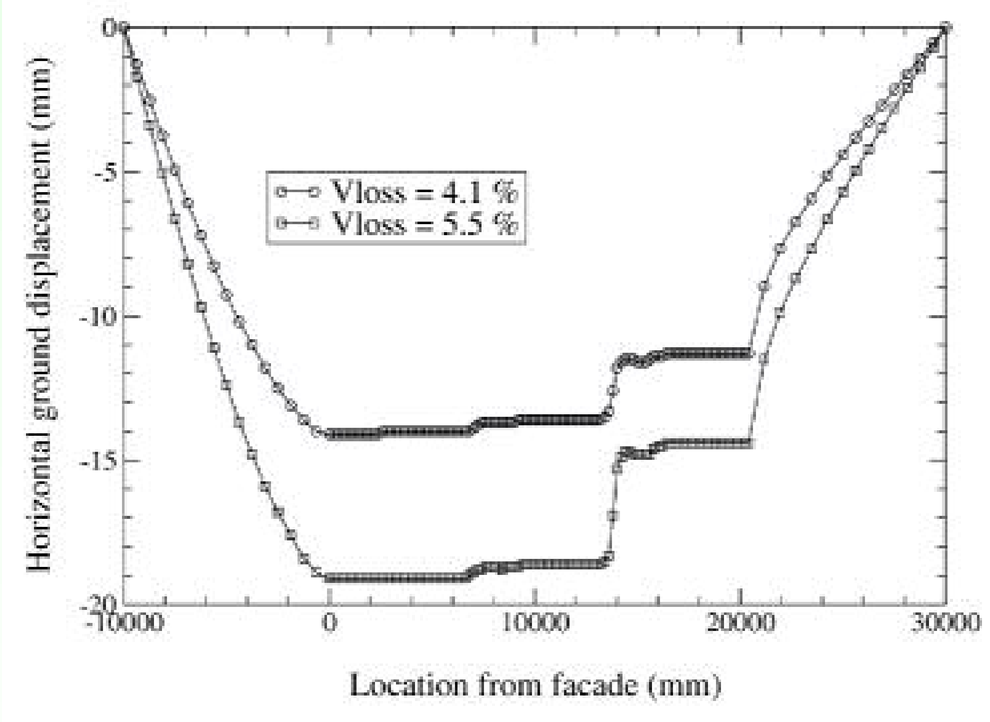
For a weak façade of little strength

Crucial damage detected in the range of typical 1-2 % ground loss in the current tunnelling practice

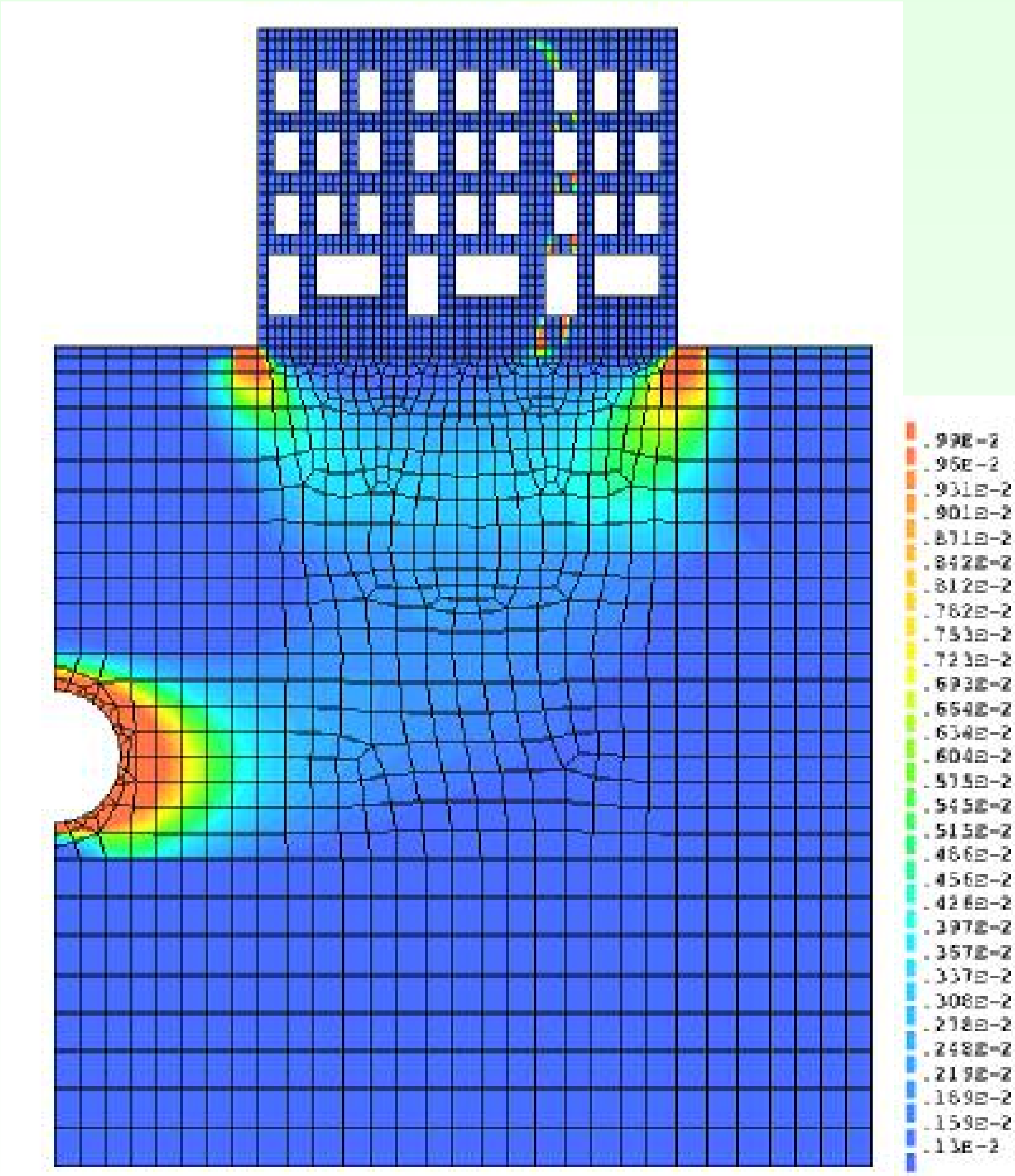


Façade response of the highly brittle material





Interacted ground response for the highly brittle façade



Example of possible settlement damage in the selected historical building by coupled analysis

Key summaries

- Promising solutions in both qualitative and quantitative aspects by fracture mechanics simulation in finite element method for this research subject

- Enhanced crack models and smart solution techniques required to achieve a better convergence and performance for the very brittle behaviour faced in large-scale fracture analysis
e.g. sequentially linear continuum concept (Rots 2002)

- Necessary future computational investigations are required to achieve the objectivity of the results together with validation of the available on-site instrumentation data