Complementary Technology

Verification – Simulation Governance

$$\lambda_{EFE} \leq \lambda \leq \lambda_{SLAB}$$

Statically Admissible
Moment Field
Hillerborg - Design

Kinematically Admissible
Collapse Mechanism
Johansen - Assessment

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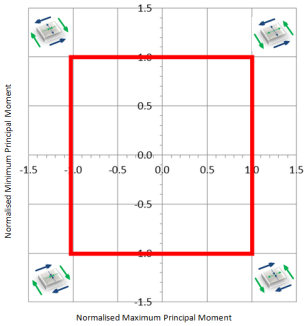
EFE – How it Works

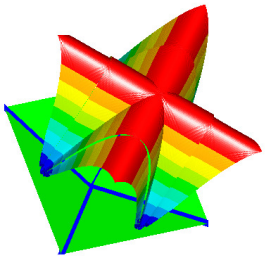
Load Factor ↓ Variables ↓

$$m = \lambda_{EFE} m_0 + \phi m_h$$

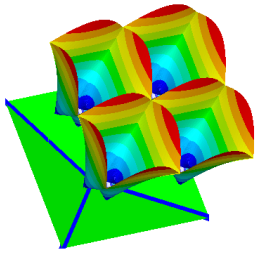
↑ Particular Moments ↑ Hyperstatic Moments



Strength Criterion



Total Solution (λ =24 - exact)



Particular Solution (λ =13.8)

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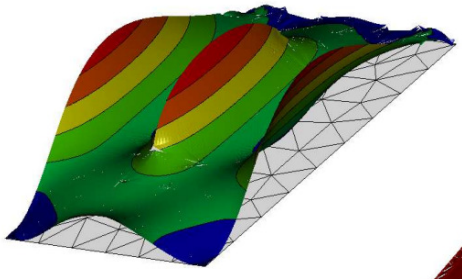
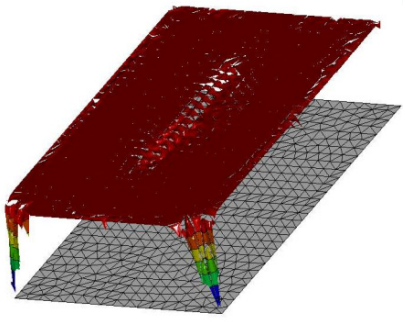
Making the Most of Your Structure



Elastic ←

Plastic →



Limit load 2.7 times load to cause first yield

Of course you will get more if you consider strain hardening and membrane action…

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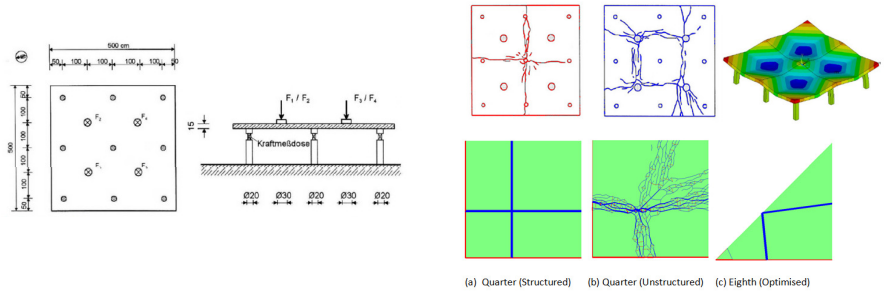
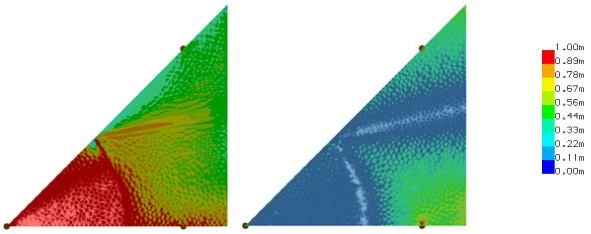
Flat Slab on Regular Array of Columns



(a) Quarter (Structured) (b) Quarter (Unstructured) (c) Eighth (Optimised)



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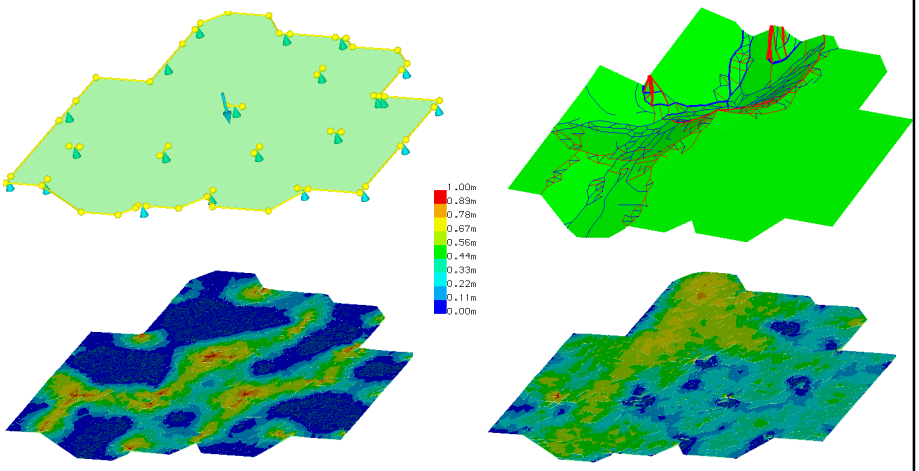
Irregular Flat Slab on Blade Columns



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EFE as a Plugin to SLAB

Initial EFE plugin to use SLAB's yield lines to delineate an initial mesh for EFE and we are confident of obtaining very close bounds to the collapse load (1% in 1 Second).

A future EFE plugin could include:

- Metallic plates,
- Elastic analysis,
- Transverse shear force fields,
- Design optimisation based on design variables as well as statical variables,
- Shakedown,
- Limited ductility in RC slabs,
- Membrane actions and the effects of large deflections.

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EFE - Admissible with Design Codes!

The **fib Model Code for Concrete Structures 2010** allows the use of the theory of plasticity in design, and this includes the "**lower bound (static) theorem**" (clause 7.2.2.4.3). However the Code appears to keep very quiet concerning the mechanics of using this theorem!

Verification of designs may be assisted by numerical simulations, including the finite element method (clause 7.11.2.2). This clause warns that "In the case of the most widely used stiffness method, the shape of the displacement field is assumed and **equilibrium is satisfied only in integral sense**. **The internal stresses are lower, compared with an exact solution**. **The approximations introduced by the finite element formulation only, can be a significant source of errors in numerical analysis**".

NB: in the lower bound plug-in, the finite element method that is used assumes fields of stresses, instead of displacements, which satisfy equilibrium exactly. Hence a source of error found in the conventional finite element method is removed.

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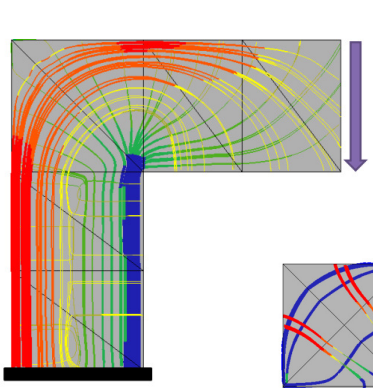
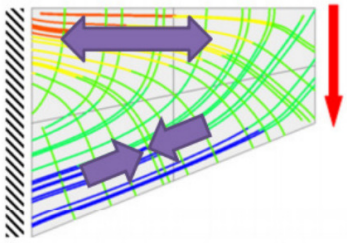
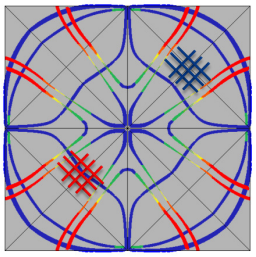
Stress Resultant Trajectories







Thank you for listening!

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