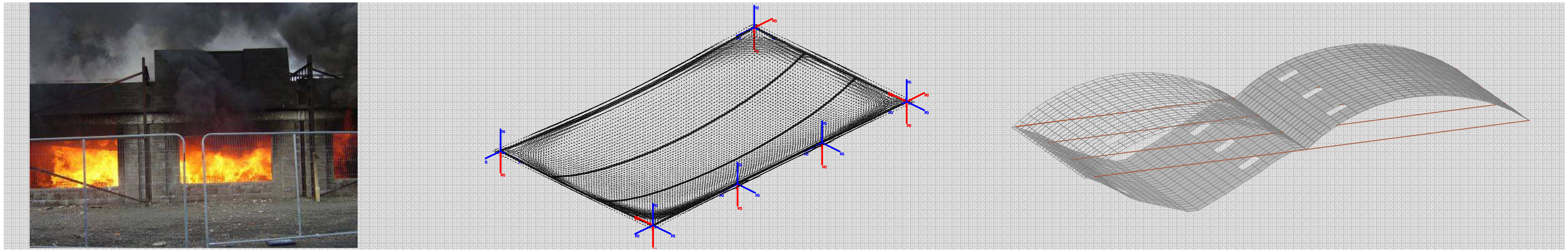
University of Liege – *Structural Engineering unit*



New developments in SAFIR 2013
New concrete models

Dr. Ir. Thomas Gernay

Secure With Steel annual meeting

Brussels – Infosteel – 29.11.2012

New developments in SAFIR 2013

1. Automatic allocation of Degrees Of Freedom (DOFs) to the nodes.

2. New material model for concrete in uniaxial stress state.

3. New material model for concrete in plane stress and in fully 3D stress states.

4. Possibility of performing 3D structural analysis with solid finite elements.
   (available material models: concrete and steel)

1. Automatic allocation of DOFs

Context: a wrong definition of the DOFs of the nodes in the input file was a usual error made by SAFIR users (ex: “floating” nodes, not attached to the structure => SAFIR did not run).

Note: CHOLESKY solver able to run despite this error but not PARDISO

The sparsity of the matrix is: 0.0070

The following ERROR was detected by PARDISO: -7

If the error is -1, then the stiffness matrix is not positive defined.

This may be due to the fact that some DoF's are not linked to the structure.

1. Automatic allocation of DOFs

Modification: automatic allocation by SAFIR.

- The number of DOFs of the nodes do not need to be declared by the user anymore.
- SAFIR allocates the number of DOFs to the nodes after examining the elements that are attached to each node.
- Only the command NDOFMAX must be present. All commands such as EVERY_NODE or FROM TO STEP NDOF are not required anymore.

✓ Simplification for SAFIR users

2. New material model for concrete 1D

New materials: SILCON_ETC ,   CALCON_ETC

- Uniaxial model for siliceous and calcareous concrete at high temperature.
- Thermal: same as SILCONC_EN or CALCONC_EN.
- Mechanical: new model with explicit computation of transient creep strain.

Use of these materials for mechanical analysis:

If CMAT = CALCON_ETC, SILCON_ETC
PARACOLD(2,NM)   Poisson ratio.
PARACOLD(3,NM)   Compressive strength
PARACOLD(4,NM)   Tensile strength

2. New material model for concrete 1D

Why defining a new concrete model?

- **Limitations** of former model
- SILCONC_EN and CALCONC_EN = model from Eurocode (EN 1992-1-2)
- Transient creep strain (TCS) included **implicitly**

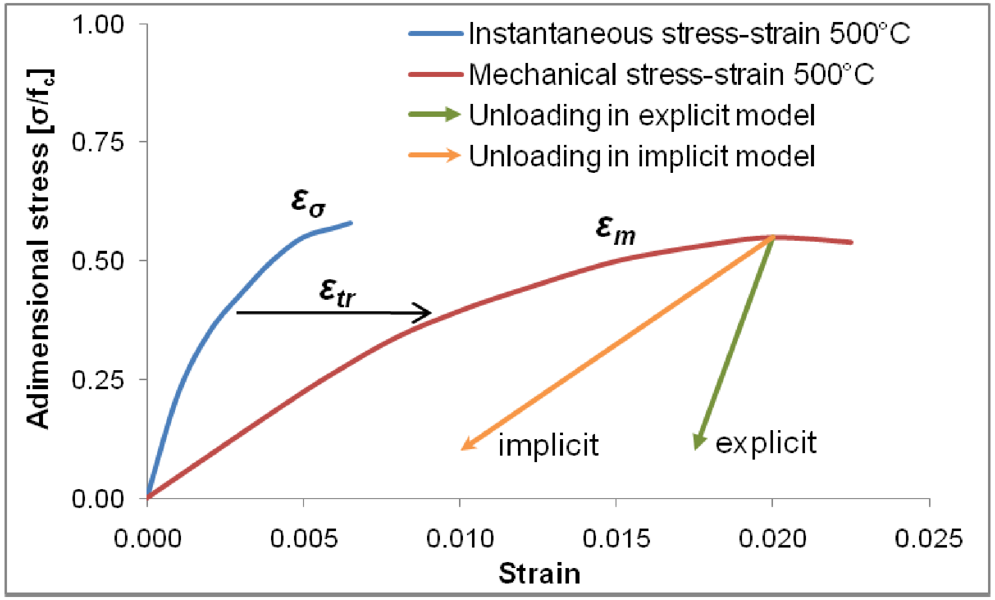
  The TCS is the additional strain that develops in concrete that is (first-time) heated under stress, compared with concrete loaded at high temperature.

- The Eurocode model is adapted for **prescriptive** design
  - Standard fire curve (heating phase only)
  - Isolated structural element

2. New material model for concrete 1D

Effect of the implicit consideration of transient creep strain

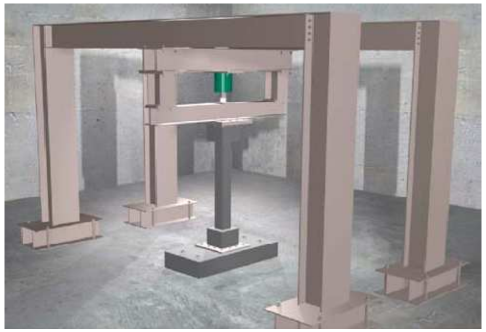
	Explicit models	Implicit models
Strain decomposition	$\varepsilon_{tot} = \varepsilon_{th} + \varepsilon_{\sigma} + \varepsilon_{tr}$	$\varepsilon_{tot} = \varepsilon_{th} + \varepsilon_{m}$
Relationship σ-ε_{tot}	depends on the "history"	univocal at given temperature
Unloading	TCS = permanent strain	TCS, not known, is recovered

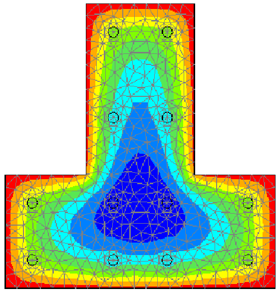


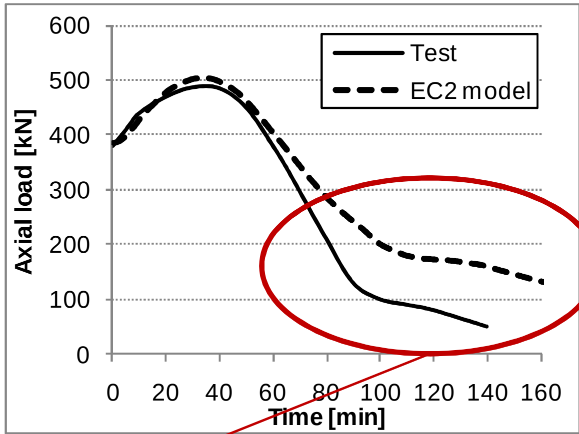
2. New material model for concrete 1D

Impact at the **structural** level

- Particularly visible in performance-based situations
- Natural fire
- Axial restraint due to the surrounding structure







The numerical simulation conducted using the implicit Eurocode 2 model fails to reproduce the behaviour of a restrained RC column during the contracting phase.

2. New material model for concrete 1D

Development of a new concrete model

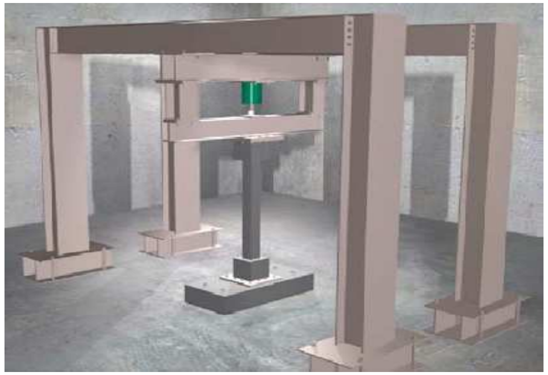
- **Explicit** model of transient creep strain should be preferred rather than implicit.
- The Eurocode 2 model, although it is an implicit model, offers several advantages: it is a generic model, proposed by experts and accepted by authorities, which gives good results for prescriptive design.

$\Rightarrow$ Decision to reformulate the Eurocode 2 concrete model with an explicit term for transient creep strain.

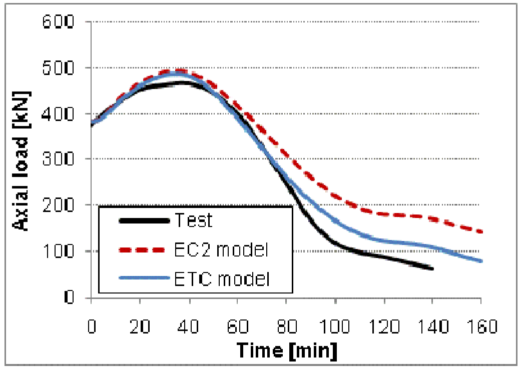
$\Rightarrow$ Explicit Transient Creep (ETC) model (= SILCON_ETC in SAFIR)

2. New material model for concrete 1D

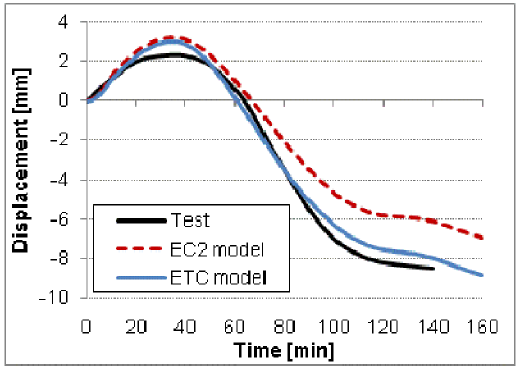
- The ETC model yields the same response as the Eurocode model in the situation of heating under constant stress (= transient test)
- In more complex situations, the ETC captures accurately the concrete behavior owing to the explicit computation of transient creep.



Axial load response



Displacement response



Conclusion: the Eurocode model was developed for prescriptive situation

the ETC model must be used in performance-based design

3. New material model for concrete in plane stress and fully 3D

<u>New materials</u>:

- Plane stress model for siliceous and calcareous concrete at high temperature:

  SILCOETC2D ,   CALCOETC2D

- Fully 3D model for siliceous and calcareous concrete at high temperature:

  SILCOETC3D ,   CALCOETC3D

- Thermal: same as SILCONC_EN or CALCONC_EN.

3. New material model for concrete in plane stress and fully 3D

New materials:

- Mechanical: new models

Use of these materials for mechanical analysis:

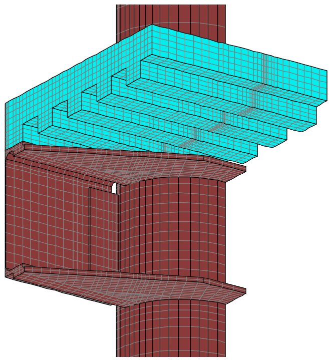
If CMAT = CALCOETC2D, SILCOETC2D or CALCOETC3D, SILCOETC3D

PARACOLD(2,NM)	Poisson ratio | Recommended value: 0.2	[-]
PARACOLD(3,NM)	Compressive strength	[N/m²]
PARACOLD(4,NM)	Tensile strength	[N/m²]
PARACOLD(5,NM)	Strain at peak stress | Recommended value: 0.0025	[-]
PARACOLD(18,NM)	Dilatancy parameter | Recommended value: 0.25 (0.20 – 0.30)	[-]
PARACOLD(19,NM)	Compressive ductility parameter | Recom. : 0.19 (0.15 – 0.25)	[-]
PARACOLD(20,NM)	Compressive damage at peak stress | Recom. 0.30 (0.18 – 0.32)	[-]
PARACOLD(21,NM)	Tensile ductility parameter | Recom.: 400	[N/m²]

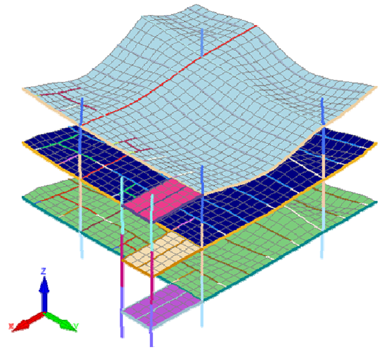
N.B. This latter parameter can be estimated as 100 [N.m/m²] / $A_e^{1/2}$ where A_e is the area of the shell element.

3. New material model for concrete in plane stress and fully 3D

- Incorporate the developments made in uniaxial situation (ETC model)
- Relationships in fully 3-dimensional stress states are required for solid FE (ex: joint model, strut and tie, shear punching)
- Relationships in plane stress states are required for shell FE (ex: structural slab model)



Numerical model by Alderighi, Univ. of Pisa, using SAFIR software.

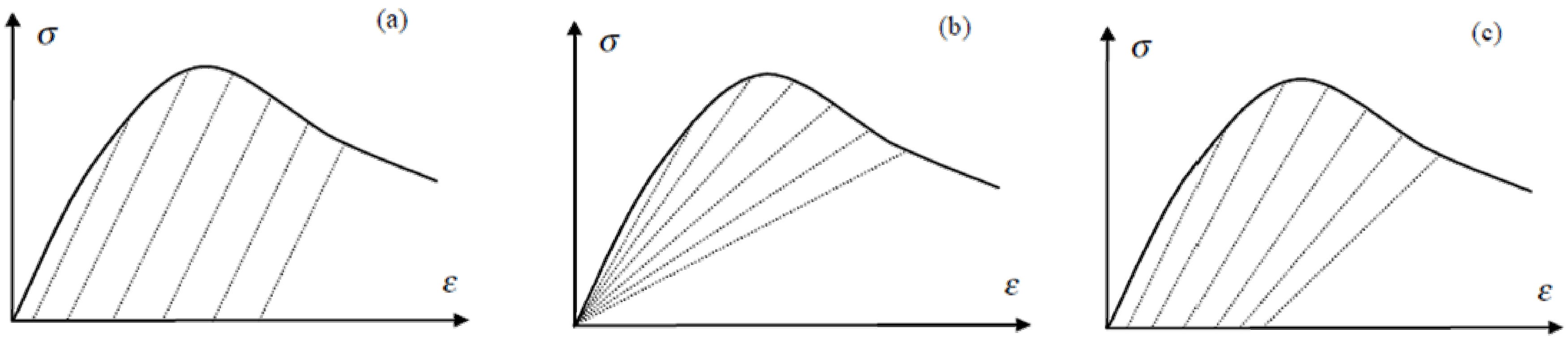


Numerical model by Fike and Kodur, Michigan State Univ., using SAFIR software.

The state of the art analysis leads to the choice of a plastic-damage model

- Continuum constitutive models based on smeared crack approach chosen for their pragmatic and robust framework (for RC applications)
- Plastic theory: dilatancy, permanent strains and hardening/softening behavior
- Damage theory: stiffness degradation and unilateral effect

$\Rightarrow$ Plastic-damage model proposed in the literature at ambient temperature (e.g. Grassl *et al*. 2006, Voyiadjis *et al*. 2009, …)

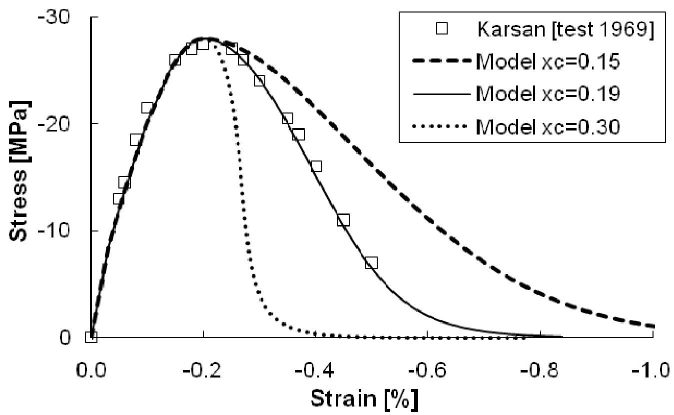


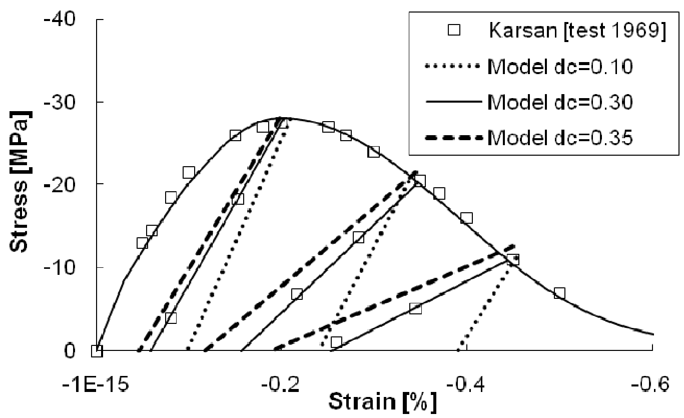
$$\underline{\underline{\sigma}} = \underline{\underline{\underline{\underline{C}}}}_0 : \left(\underline{\underline{\varepsilon}}_\sigma - \underline{\underline{\varepsilon}}_p\right) \qquad \underline{\underline{\sigma}} = (1-d)\,\underline{\underline{\underline{\underline{C}}}}_0 : \underline{\underline{\varepsilon}}_\sigma \qquad \underline{\underline{\sigma}} = (1-d)\,\underline{\underline{\underline{\underline{C}}}}_0 : \left(\underline{\underline{\varepsilon}}_\sigma - \underline{\underline{\varepsilon}}_p\right)$$

The model contains 10 material parameters

- Calibration from 3 simple tests
- Standard values for predictive calculations → generic
- Physical meaning

Parameter	Name	Units	Required test
ν	Poisson's ratio	[−]	Uniaxial compression
f_{c0}	Compr. limit of elasticity	[MPa]	Uniaxial compression
f_c	Uniaxial compr. strength	[MPa]	Uniaxial compression
ε_{c1}	Peak stress strain	[−]	Uniaxial compression
α_g	Dilatancy parameter	[−]	Uniaxial compression
x_c	Compr. dissipated energy	[−]	Uniaxial compression
$\tilde{d}_c$	Compr. damage at peak stress	[−]	Uniax. compr. + unloading
f_b	Biaxial compr. strength	[MPa]	Biaxial compression
f_{t0}	Uniaxial tensile strength	[MPa]	Uniaxial tension
g_t	Tensile crack energy density	[MPa]	Uniaxial tension





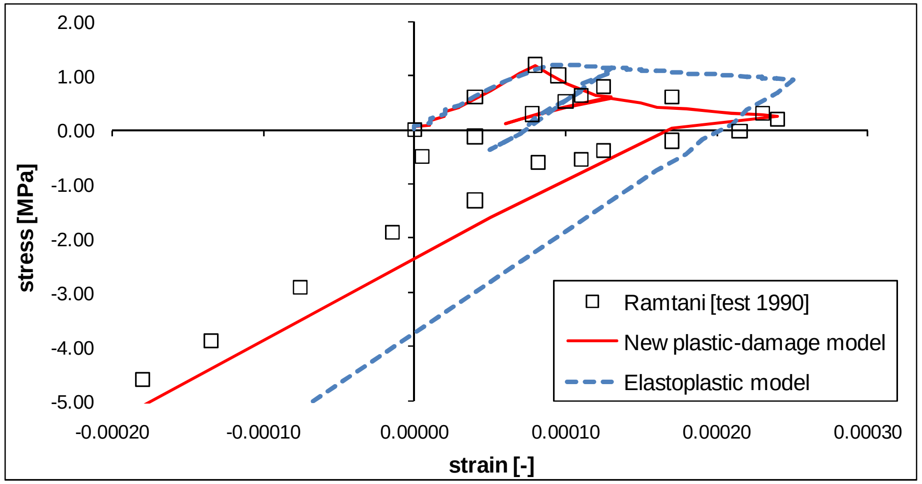
Improvements - new model VS former model in SAFIR

Specification	Former SAFIR model*	New model
Unilateral effect	Plastic model	Plastic + Damage
Concrete dilatancy	Associated plasticity	Non-associated plasticity
Transient creep strain is irrecoverable	TCS implicitly recovered	Explicit transient creep model (original ETC model)
Confinement effect	Von Mises in compression (no hydrostatic component)	Drucker-Prager in compression
Numerical robustness	Could be improved	Special care to the numerical integration of the constitutive laws
Dimension of the model	2D plane stress	3D (→2D plane stress)

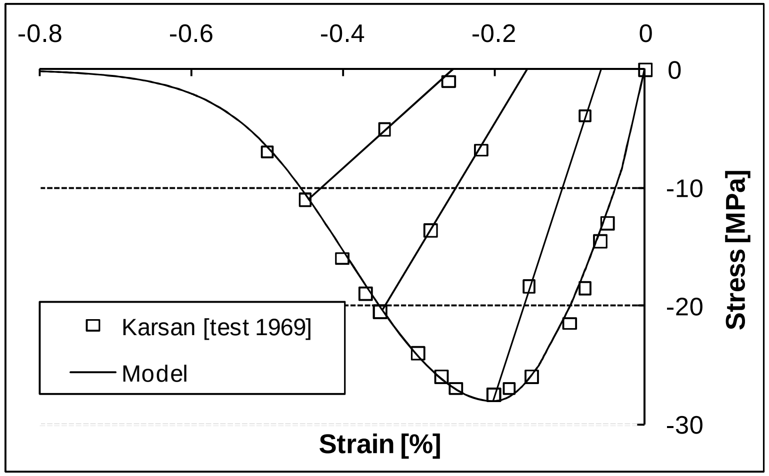
* model implemented by D. Talamona, based on the analysis by C. Doneux.

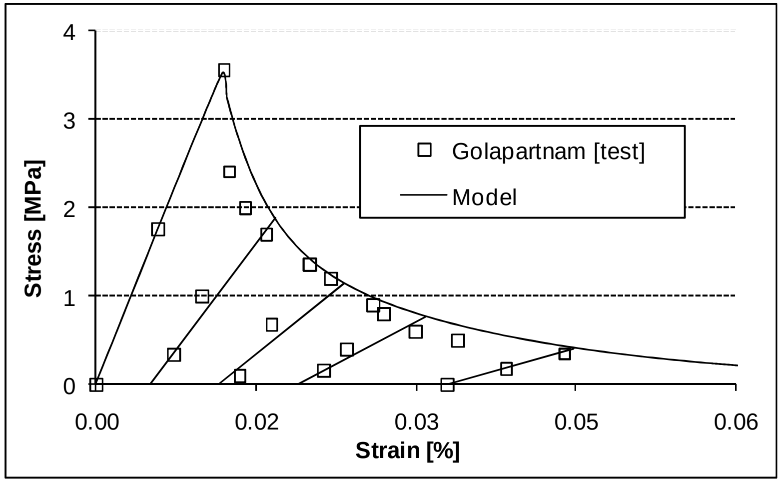
Examples of application
Material level – ambient temperature

Unilateral effect



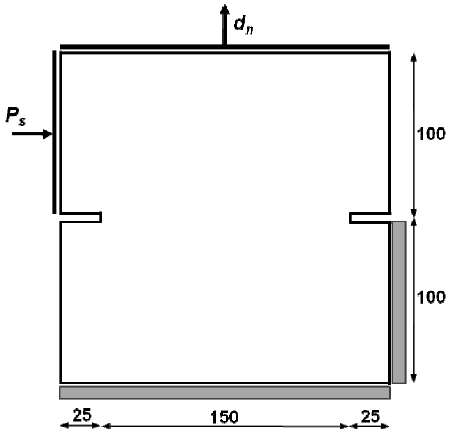
Loading-unloading in compression and tension

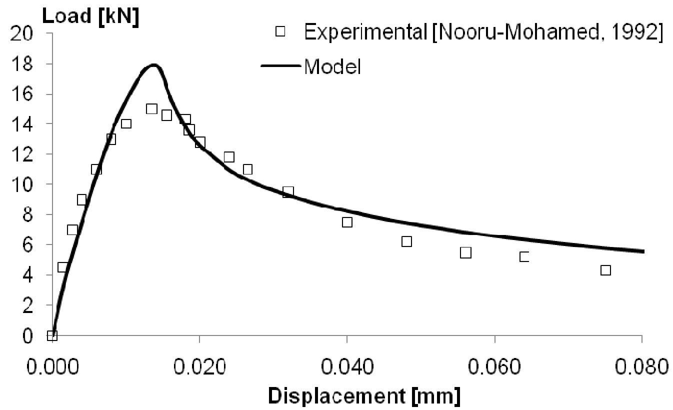




Ambient temperature
Mixed mode fracture of plain concrete

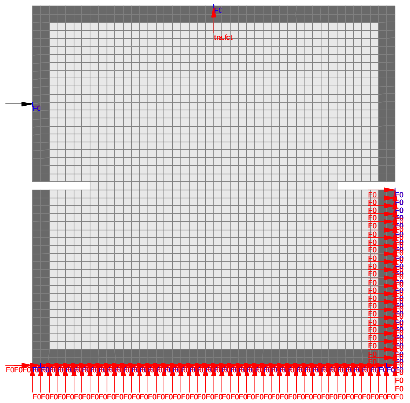
Nooru-Mohamed test, 1992
Application of shear force, then positive tensile displacement until failure

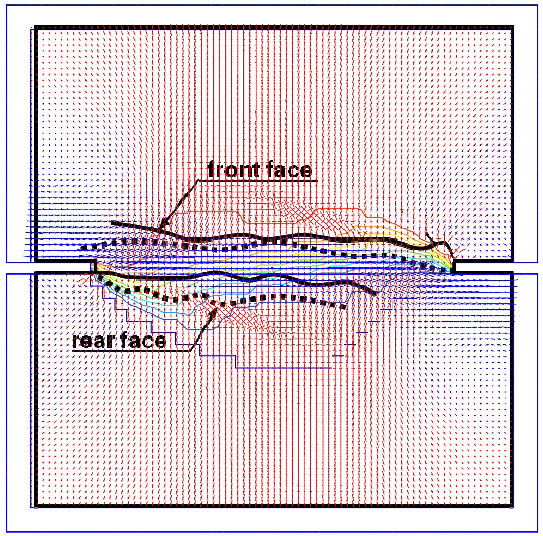




Load-displacement diagram
Experimental VS SAFIR model

SAFIR finite elements model



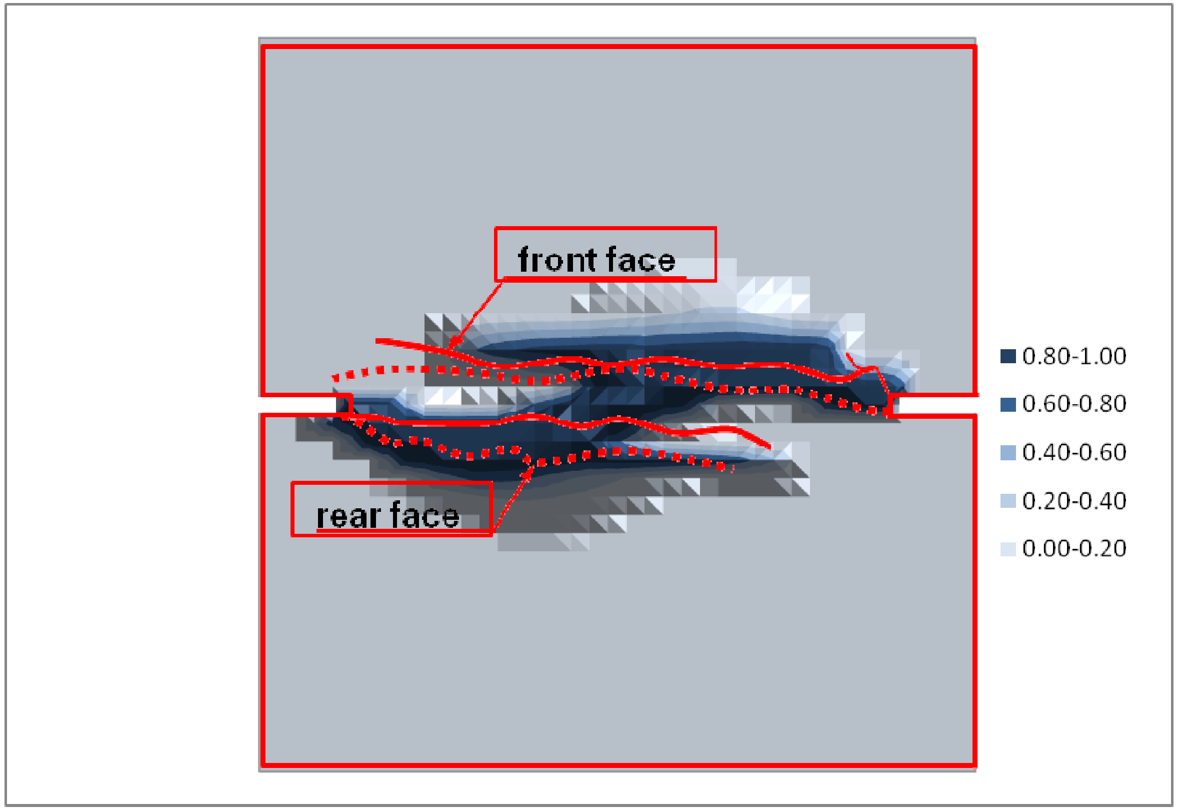


Crack pattern (end of the test)
Experimental results

VS

SAFIR model displacements
SAFIR membrane forces
(isolines of the displacements)

Tensile damage pattern
Mixed mode fracture of plain concrete

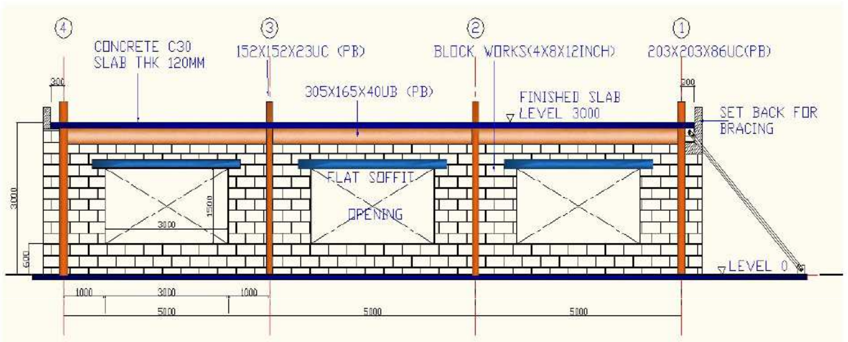


Application to structures in fire: Modeling the Ulster fire test

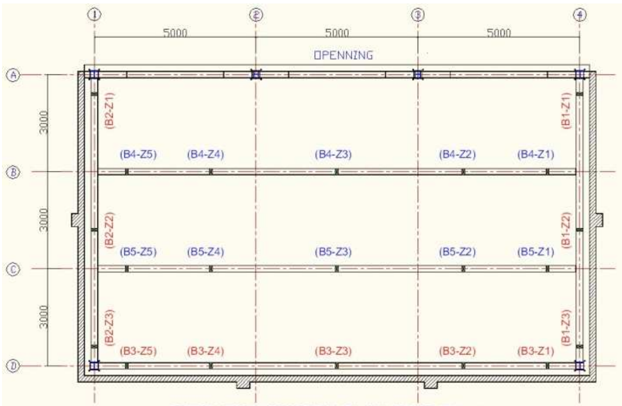
Full scale fire test performed on 27/02/2010 in Ulster (RFCS project – Vassart *et al., 2011*)

Application to structures in fire: Modeling the Ulster fire test

- Dimensions of the compartment: 15 m by 9 m



- Steel concrete composite slab supported by cellular steel beams

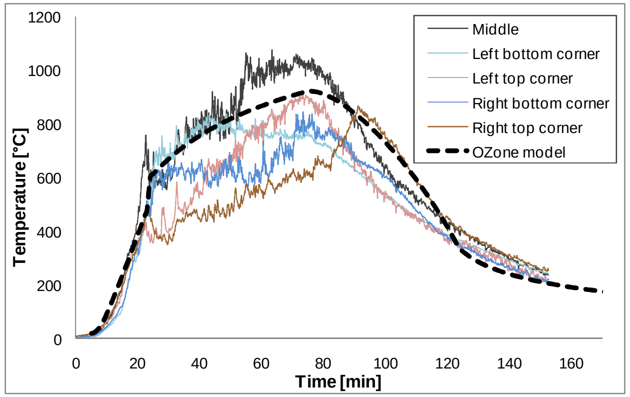


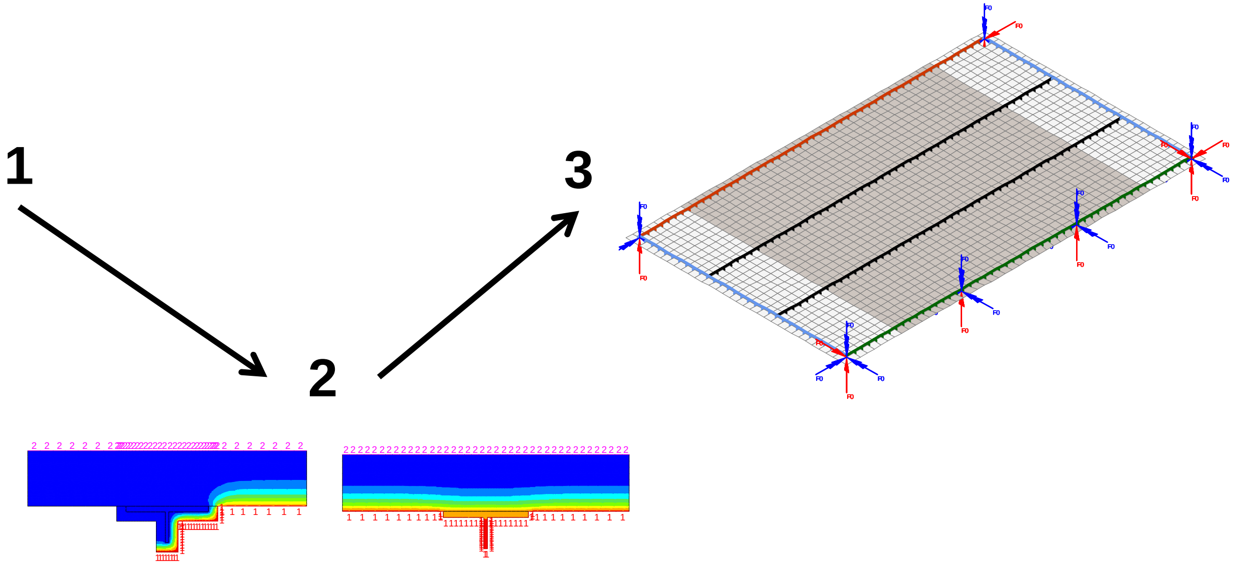
Application to structures in fire: Modeling the Ulster fire test

- No thermal protection over the two central steel beams (objective: investigate the development of tensile membrane action)
- Natural fire put in the compartment

Numerical modeling of the test

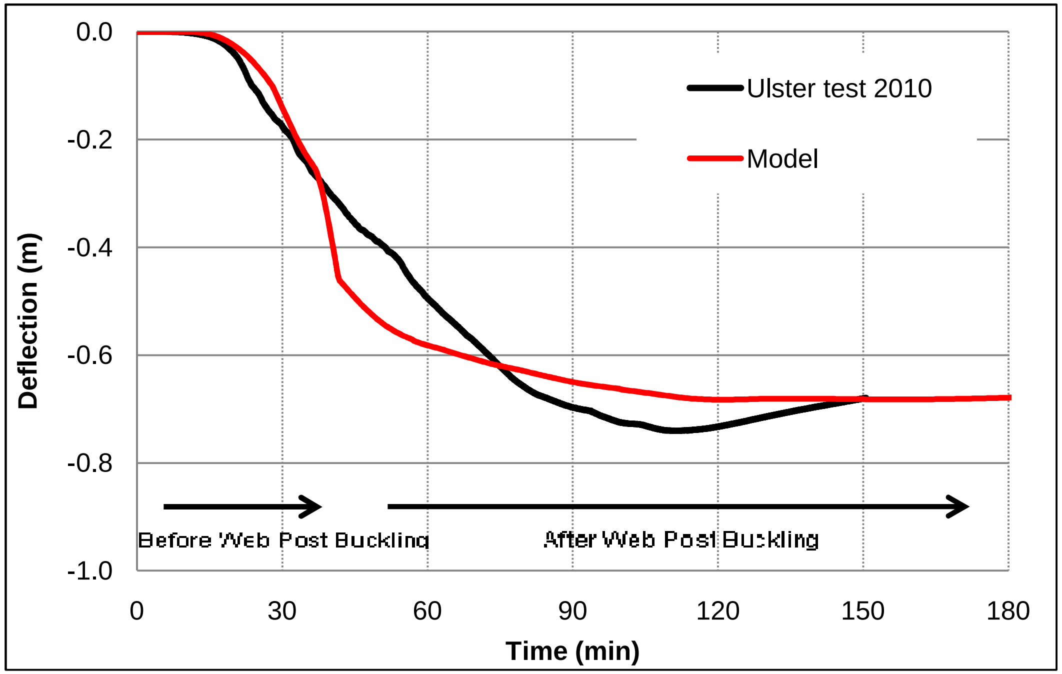
1. Model of the fire to get the temperatures in the compartment
2. Thermal analysis of the sections
3. Mechanical analysis of the structure





The blind numerical simulation is able to predict the behavior

- Evolution of the vertical deflection of the central unprotected steel beam
- Qualitatively good correspondence between computed and measured results, although it was a blind simulation



Experimental observations

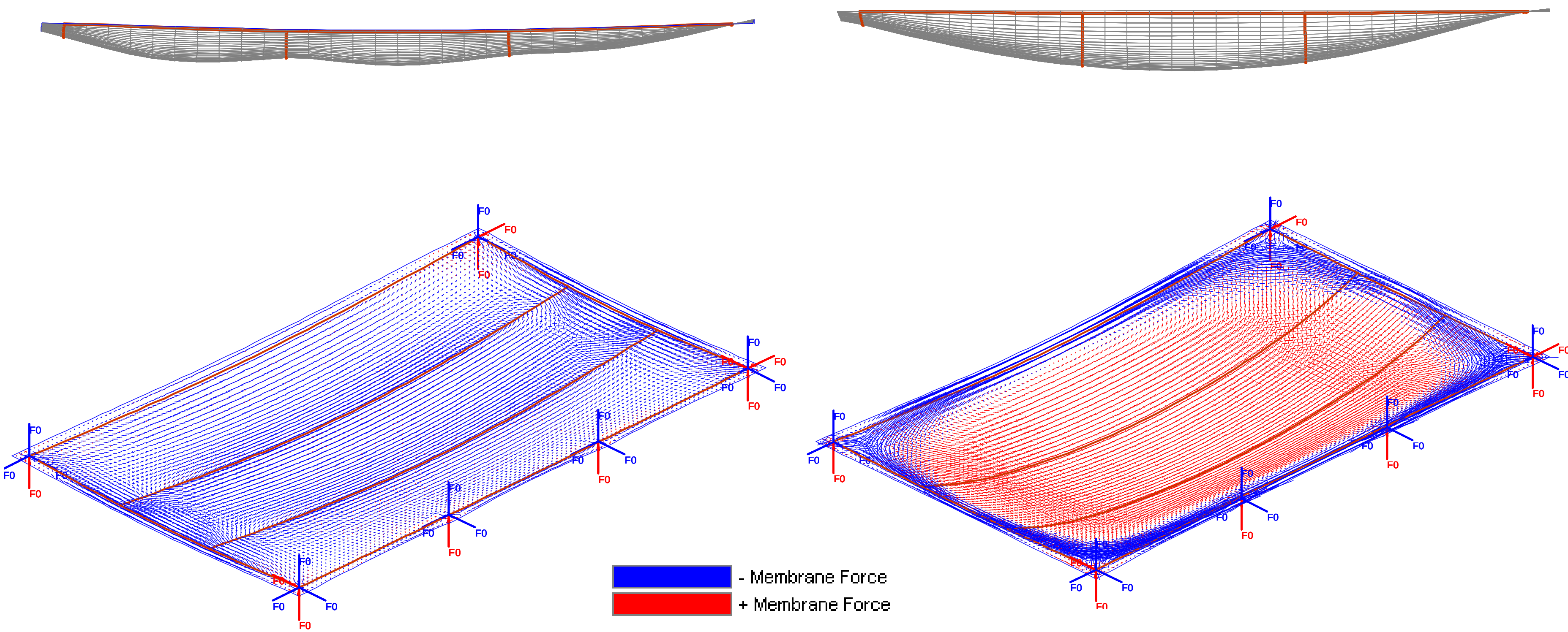
Tensile membrane action

Web post buckling

The simulation captures the development of membrane action

Room temperature

Fire situation



4. Structural analysis with solid FE

Now possible in SAFIR (v. 2013)

Available material models

- SILCOETC3D , CALCOETC3D for concrete
- STEELEC23D , STEELEC33D for steel

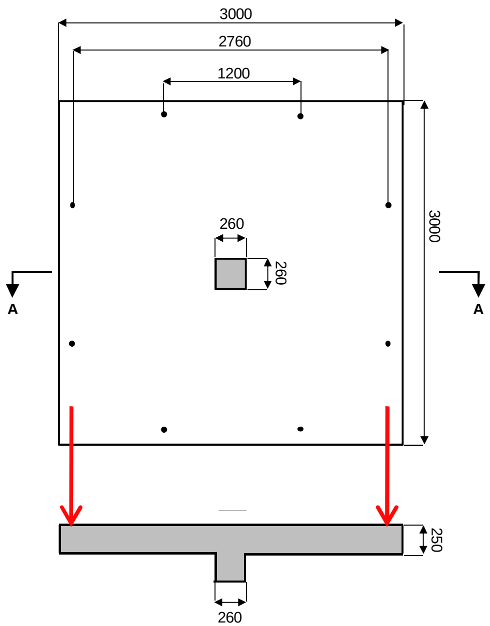
Thermal and mechanical models for steel solid FE

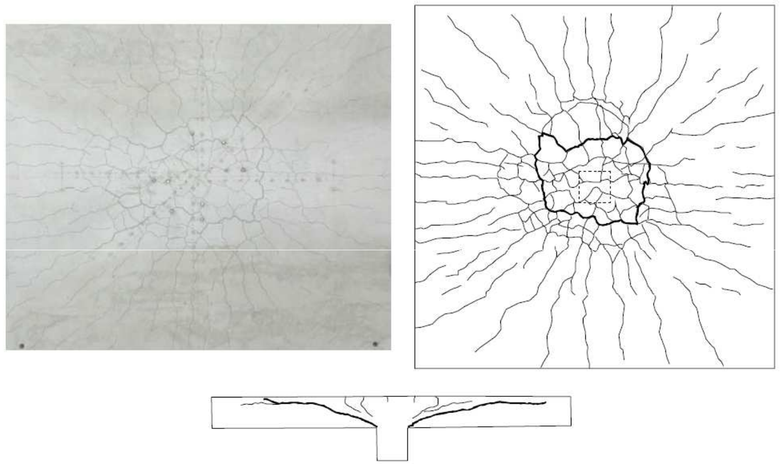
Use of these materials for thermal analysis: same as STEELEC3EN

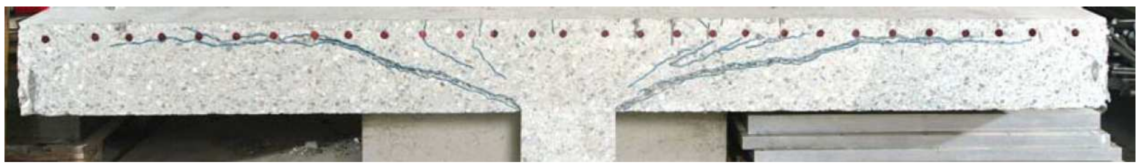
Use of these materials for mechanical analysis: same as STEELEC32D

Perspectives: analysis of problems with 3D stress states

Shear punching in a flat slab at ambient temperature: tests at EPFL (Guandalini, 2006)

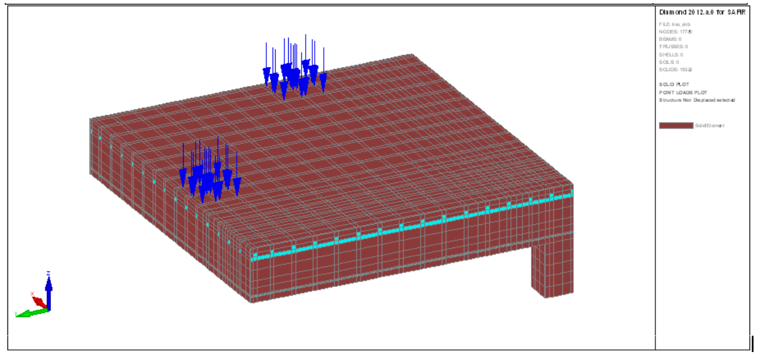


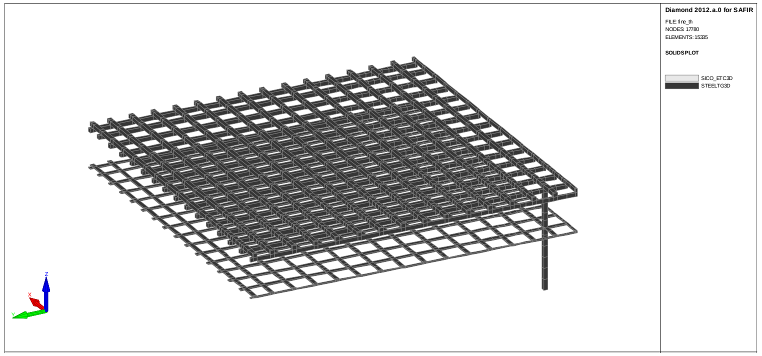




The concrete model can be used to study shear punching.

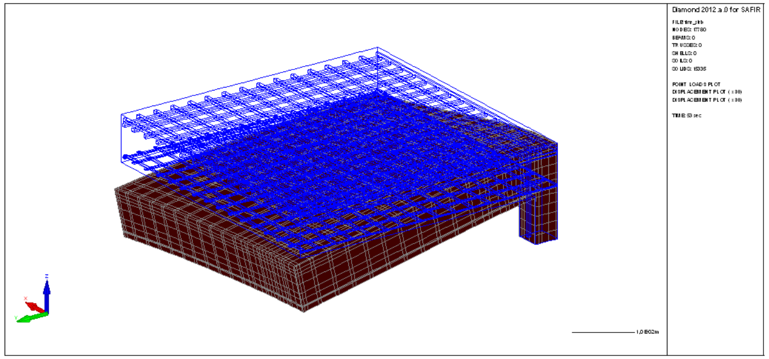
- Model using 3D solid FE for the concrete slab and for the steel rebars

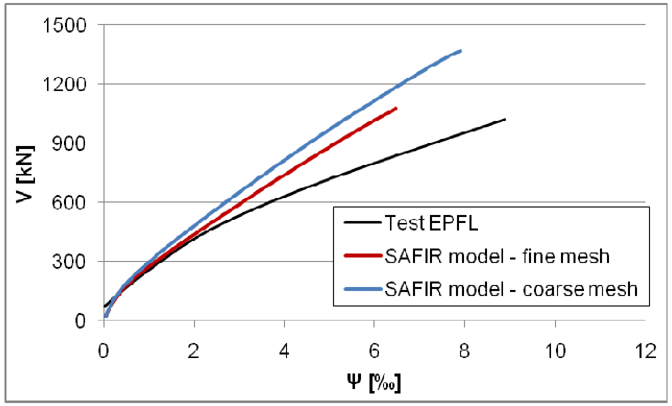




- Possibility to analyze such problems with fully 3D analysis
- Influence of the mesh in the results, model size limitation (17,780 nodes)

=> Interesting perspective but developments needed (pre- and post-processor, …)





Summary

New developments in SAFIR 2013

1. Automatic allocation of Degrees Of Freedom (DOFs) to the nodes.

2. New material model for concrete in uniaxial stress state.

3. New material model for concrete in plane stress and in fully 3D stress states.

4. Possibility of performing 3D structural analysis with solid finite elements.
   (available material models: concrete and steel)

Additional information

Uniaxial ETC concrete model

- Gernay, T. and Franssen, J.M., A formulation of the Eurocode 2 concrete model at elevated temperature that includes an explicit term for transient creep, *Fire Safety Journal*, 51, pp. 1-9, 2012.
- Gernay, T., Effect of Transient Creep Strain Model on the Behavior of Concrete Columns Subjected to Heating and Cooling, *Fire Technology*, 48(2), pp. 313-329, 2012.

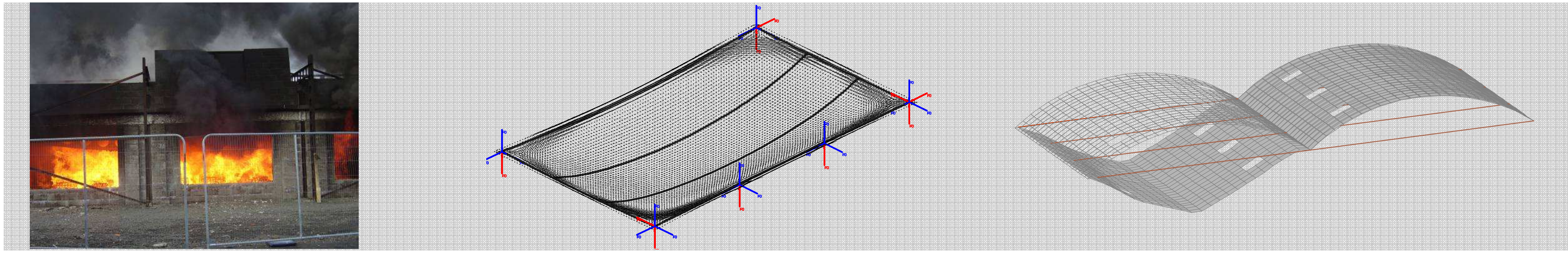
Multiaxial concrete model

- Gernay, T., A multiaxial constitutive model for concrete in the fire situation including transient creep and cooling down phases, Ph.D. thesis, University of Liege, 2012.
- Gernay, T. and Millard, A., A multiaxial concrete model for applications in structural fire engineering, *Proceedings of the 7th International Conference on Structures in Fire*, ETH Zurich, June 6-8 2012, pp. 531-540.

Use of SAFIR 2013

- SAFIR 2013 user manual

University of Liege – *Structural Engineering unit*



New developments in SAFIR 2013
New concrete models

Dr. Ir. Thomas Gernay

Thank you for your kind attention

Secure With Steel annual meeting

Brussels – Infosteel – 29.11.2012