Evaluation of Structural Fire Performance. Today and Tomorrow

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Content

- Modelling of 3D structures
- Joints in steel structures
- Spalling in concrete structures
- Cellular beams
- Tensile membrane action
The detailed 3D discretisation and analysis of a complex structure made of numerous bars is not practically feasible.

Solution: series of uncoupled sub-structure analyses
Modelling of 3D structures
Modelling of 3D structures

Structural analysis of the secondary frame

Reactions to the primary frames

Failure Mode of the secondary frame
Modelling of 3D structures

Application of reaction to the primary frames

Reactions from secondary frames
Modelling of 3D structures

Application of reaction to the primary frames

Failure Mode of the primary frame
Test « FLUMILOG », courtesy INERIS, France
Diamond 2009.a.5 for SAFIR

FILE: Modelo_Def_3
NODES: 2624
BEAMS: 940
TRUSSES: 0
SHELLS: 0
SOILS: 0

DISPLACEMENT PLOT (x 1)
TIME: 739.0464 sec
Joints in steel structures

Introduction to the problem

Until recently, the behaviour of steel joints under fire conditions has not been investigated because:

- The fire resistance of steel structures is usually calculated under fire curves with no cooling phase.
Joints in steel structures

Introduction to the problem

Until recently, the behaviour of steel joints under fire conditions has not been investigated because:

- Due to the presence of more material, temperature in joint is lower than in the connected members.
Joints in steel structures

Introduction to the problem

Until recently, the behaviour of steel joints under fire conditions has not been investigated because:

- The joints are usually designed to be more resistant than the connected members at room temperature.
Joints in steel structures

**Introduction to the problem**

However, failures in joint components have been observed experimentally during the cooling phase of natural fires:
Introduction to the problem

Joint failures occur during the cooling phase of natural fires because:

- During the cooling phase, large tensile forces are generated in axially restrained beams.
Joints in steel structures

Introduction to the problem

Joint failures occurs during the cooling phase of natural fires because:

- The resistance of bolts and welds reduces quicker than carbon steel at elevated temperatures and is not reversible during the cooling phase (EN 1993-1-8)
Joints in steel structures

Numerical Modelling of Joints – Thermal analyses
Numerical Modelling of Joints – Structural Analyses

- Fibre Models based on the Component Method
Joints in steel structures

Numerical Modelling of Joints

- Material Laws working in tension/compression or asymmetric
Joints in steel structures

Numerical Modelling of Joints

- Laws with descending branch to include the risk of failure
Joints in steel structures

Tests performed at University of Sheffield

Comparisons between experimental and numerical rotations

\[ \alpha = 55^\circ \]
Joints in steel structures

Tests performed at University of Sheffield

Comparisons between experimental and numerical rotations

\[ \alpha = 35^\circ \]
Spalling in concrete structures

Under high temperatures, concrete layers spalls
Spalling in concrete structures

Introduction to the problem

Under high temperatures, concrete layers spalls
Spalling in concrete structures

Analysed Structure

![Diagram of an analysed structure with dimensions and axes labeled.]
Spalling in concrete structures

Fire Scenario: Courbe HCM

SFPE Handbook

$T^o(x)$ for a 200 MW fire

Fire source

Burning truck
Spalling in concrete structures

Results of tests and Assumptions

Unfavour. Case:

Realistic Case:

3 mm/min during 30 min
Spalling in concrete structures

Integration of spalling

Minute $i$

HCM

20 °C

Minute $i+1$

HCM

3 or 7 mm-thick concrete layer

Rebars are removed simultaneously with concrete of the same level
Spalling in concrete structures

Results

Failure Mode with & without spalling

![Graph showing vertical displacement vs. time for different spalling rates.]

- Spalling 0 mm/min
- Spalling 3 mm/min
- Spalling 7 mm/min

<table>
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<th>Vertical Displacement (m)</th>
<th>Spalling 0 mm/min</th>
<th>Spalling 3 mm/min</th>
<th>Spalling 7 mm/min</th>
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</table>
Spalling in concrete structures

Fire Resistance with partial protection
Cellular beam – steel beam

**Model**

- 4-node shell finite elements
Cellular beam – steel beam

Initial deformation

- To obtain local buckling
- Sine curve on the height of the profile
- Cosine curve on the length of the beam

Amplitude maximum = 2 mm
Cellular beam - Composite beam – Full connection

**Model**
- 4-node shell finite element for the steel profile
- Beam element for the concrete slab

**Diagram**
- Full connection
- The concrete slab beam and the steel upper flange have common nodes

**Notes**
- beam F.E. for concrete slab
Cellular beam - Composite beam - Partial connection
Stud model

- Model 1: the number of equivalent studs is equal to real number of studs
- Model 2: an equivalent stud is placed on each node of the upper steel flange
- Model 3: idem than model 2 but the equivalent stud section is numerically improved.
Stud model

- Stud model 1
- Stud model 2
- Stud model 3
Cellular beam - Composite beam - Partial connection

![Graph showing stress-strain characteristics](image)

- Full Connexion
- M1
- M2
- M3
- Without Connexion

**Load [kN/m]**

**Vertical displacement mid-span [mm]**

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**BuildSoft**

la maîtrise du calcul
Cellular beam in case of fire: example

Diagram showing the deflection over time for Test B2 and Safir Simulation.
Cellular beam in case of fire: example
Cellular beam in case of fire: example
Tensile Membrane Action

Room temperature

Fire Situation
How is the load supported?

• The unprotected central steel beams lose all strength and stiffness.
• The slab behaves as a membrane.
• High deflections are reached in order to equilibrate vertical loads.
• The slab is highly cracked and the steel mesh is in tension.
• The tension in the central part is equilibrated by a compression ring within the slab.
Example: administrative building of ArcelorMittal in Flémalle
A full scale test, somewhere in Europe
Result?

So what?
Full scale fire test (Ulster)  
RFCS research « FICEB »

• Natural fire in a compartment of 9m by 15m
• Composite slab supported by two central unprotected beams
• Peripheral protected beams
Fire development

First step: to model the fire that will develop in the compartment (Ozone)

Fire load by 45 standard wooden crips (33 kg/m²)
Fire development

OZone software

This calculation gives the gas temperature as a function of time in the compartment.
Thermal analysis of the beams

Central beams (1) are unprotected
Thermal analysis of the beams

- Edge beam (1) is protected
- Attacked by the fire only on one side
Thermal analysis of the beams

• Edge beam (3) is protected
• Attacked on one side
Thermal analysis of the beams

- Beams (2) are protected
- Attacked on one side
Thermal analysis of the slab

- Composite slab with steel deck
- The steel deck is not modeled and the geometry of the slab is simplified
Thermal analysis of the slab

- The concrete in the ribs is partially considered for thermal analysis because it absorbs part of the heat (thermal analysis => effective thickness)
- Only the cover part of the slab is considered for structural analysis (structural analysis => only the cover thickness)
Structural analysis – room temperature

- Beam elements were used for the beams and shell elements for the slab
- The uniformly distributed load is increased until collapse.
- The structural behaviour is a bending mode
Structural analysis – fire situation

Structural behaviour totally different compared to the cold case: the unprotected beams lose their stiffness and the slab develops a tensile membrane action.
44 bags of 1 ton on the roof => 330 kg/m²
Facility: Fire Lab

Horizontal furnace

- Dimensions: 3 m x 4 m
- Max. load: 100 t
- Ceilings, slabs, floors, beams, roofings.
Facility: Fire Lab

Vertical furnace

- Dimensions: 3.25 m x 3.25 m
- Max. load: 300 t
- Dividing walls, structural walls, doors, façades, electric cables.
Thank you.