The Real Behaviour of Buiding Structures in Fire – Implications for Design and Research

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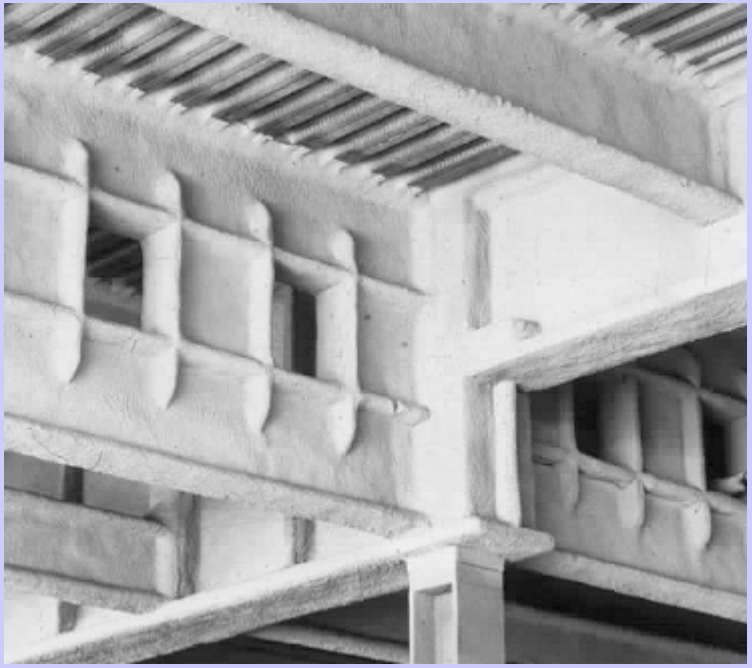
Applied fire protection

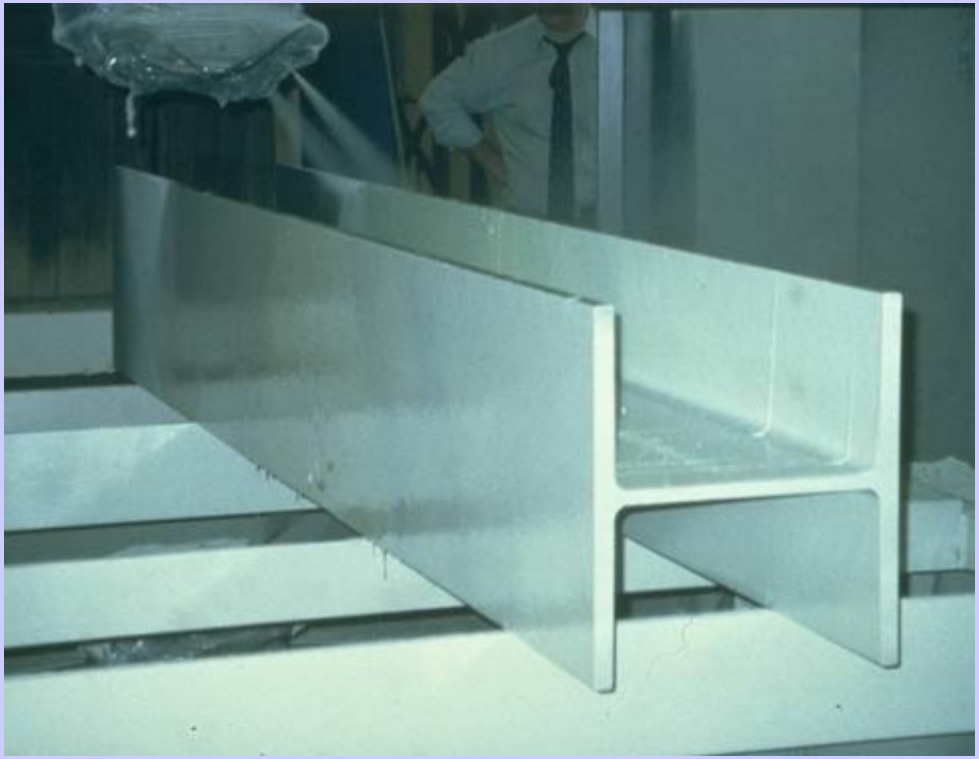


Intumescent coatings

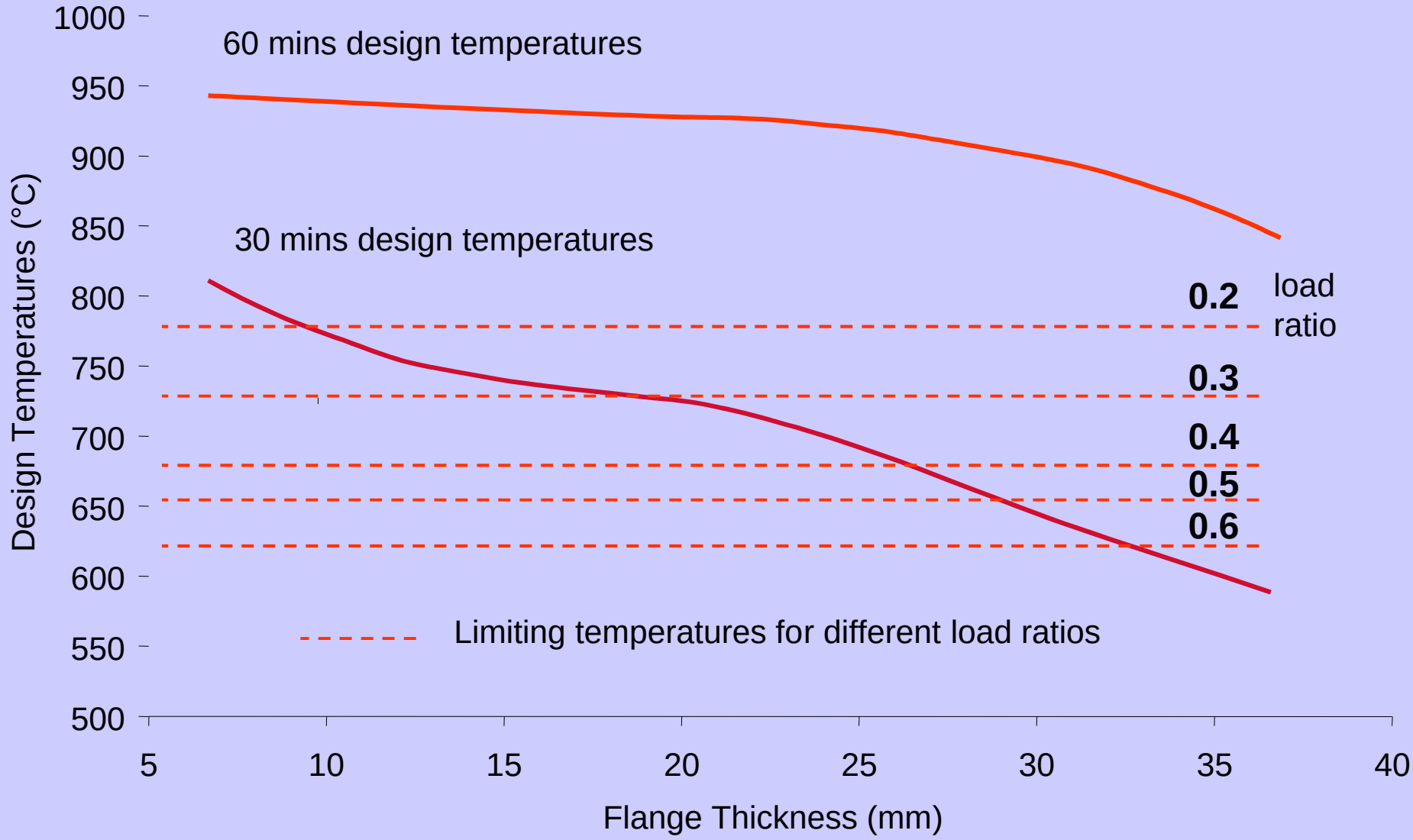
- Recent developments:
  - Reduced costs
  - Improved performance
  - Development of off-site application
- Market share increased from 7% to 40%

Off-site Protection

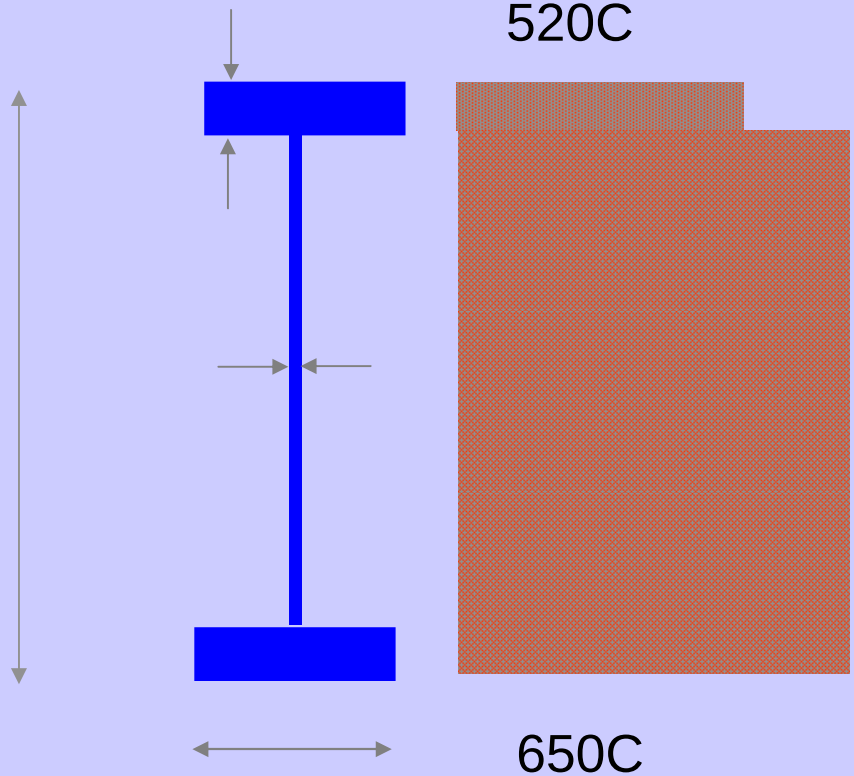
Saves time on site
Reduces overall cost



Limiting Temperature Method

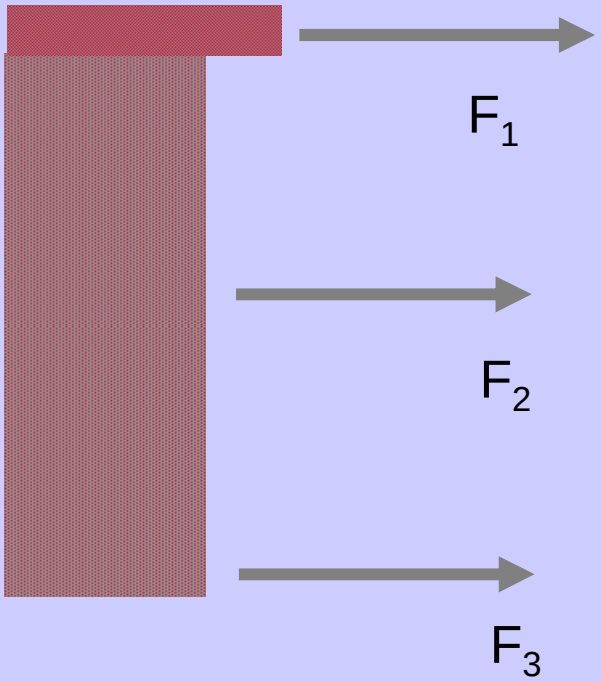


Moment Capacity Method



Temps

$f_y = 0.72 \times 275 = 198$ MPa



$f_y = 0.35 \times 275 = 96$ MPa

Stresses

Application of simple methods

Stock Orchard St

Steel framed

P/C joist + block floor

- No composite action
- No membrane action

But…

- Some shielding
- Low load ratios

Beams and columns treated as simple isolated elements

Outcome:

Most elements unprotected

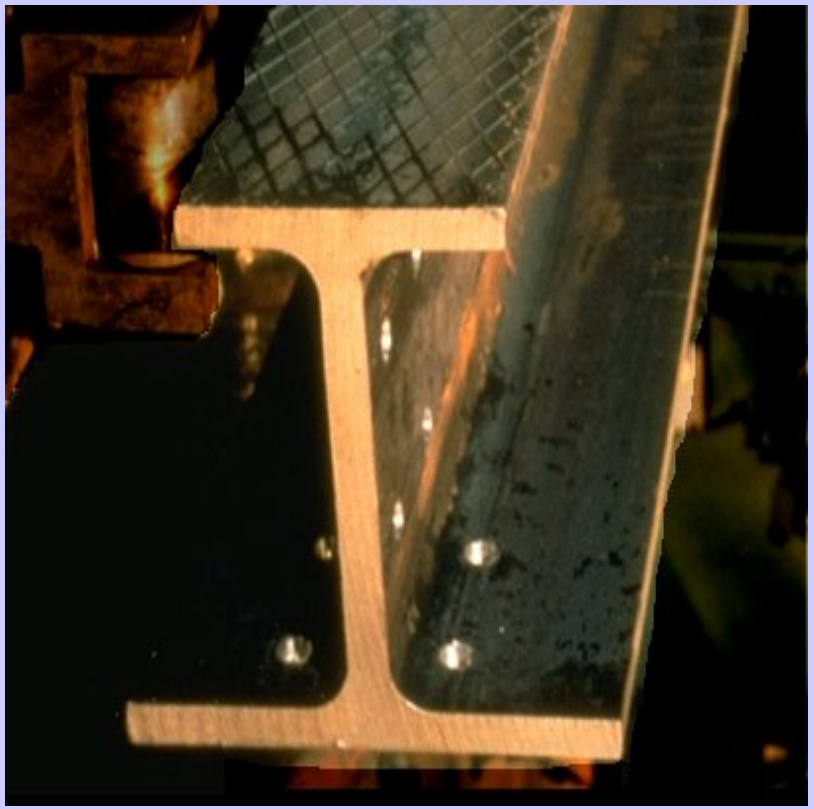
Significant cost savings

Corporate HQ

- A/s steel beams 12.6m span
- Haunched precast floor slabs
- External steelwork exposed
- 60 minute fire period

‘Slimfloor’ construction

- Becoming popular
- Provides implicit protection



Asymmetric Slimflor Beam (ASB)

Manufactured as standard

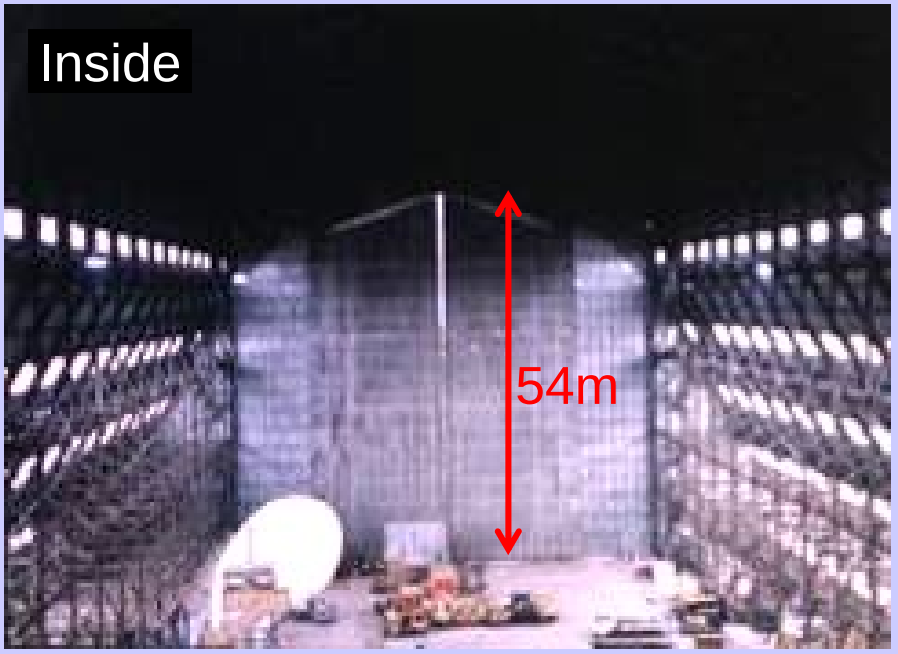
Broadgate Phase 8, London

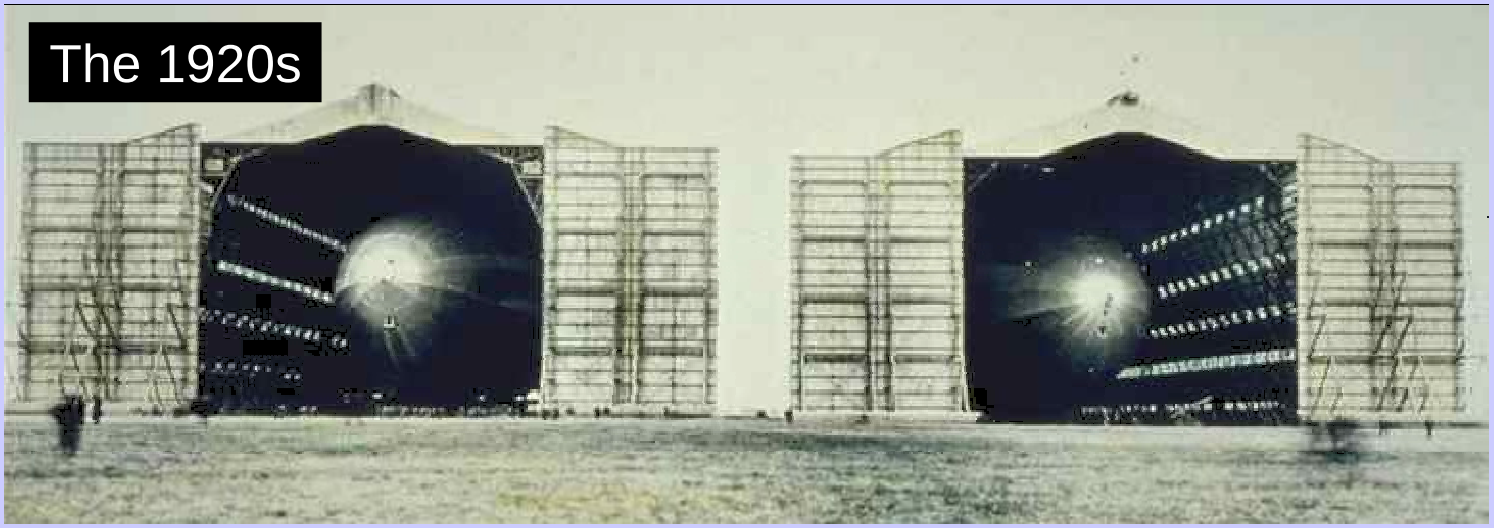
- 4½ hours' duration
- Unprotected steel
- Total cost of fire £20m
- Structural repair cost £1.5m

Real structures more fire-resistant than simple rules suggest?

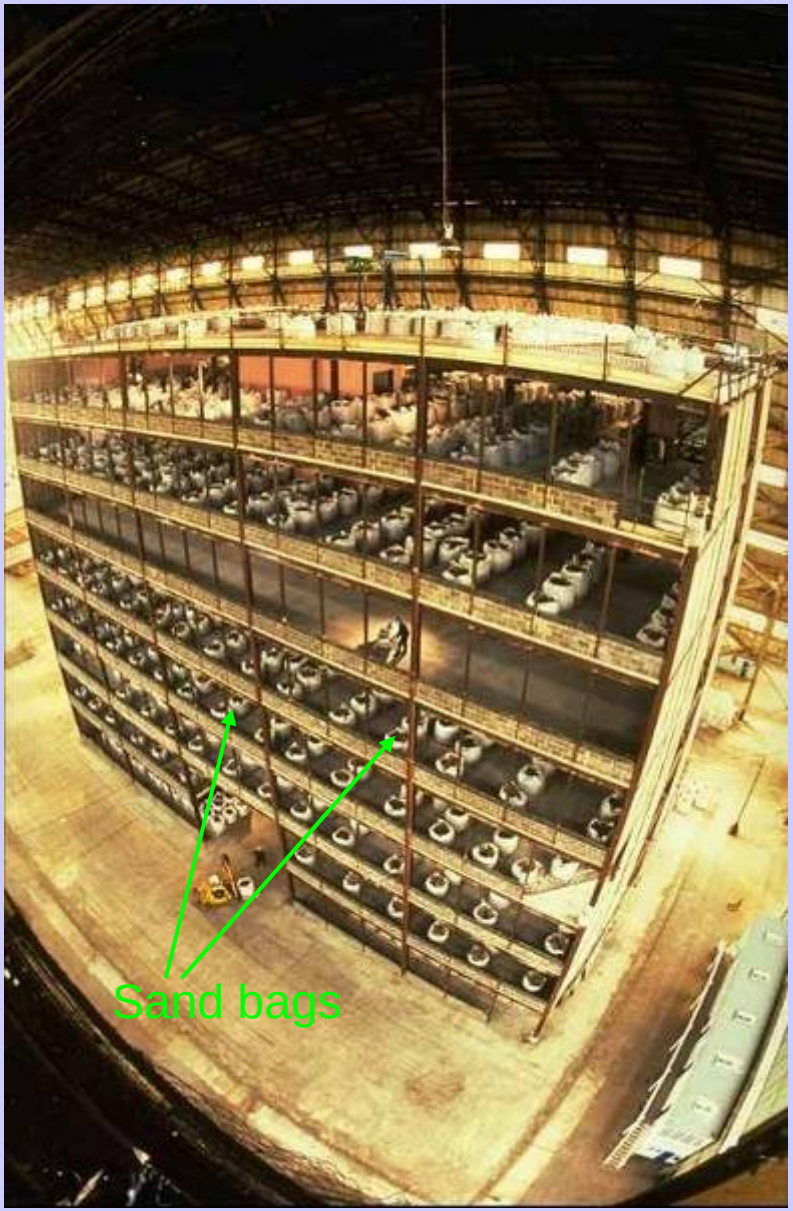
Cardington research programme

The BRE Cardington laboratory

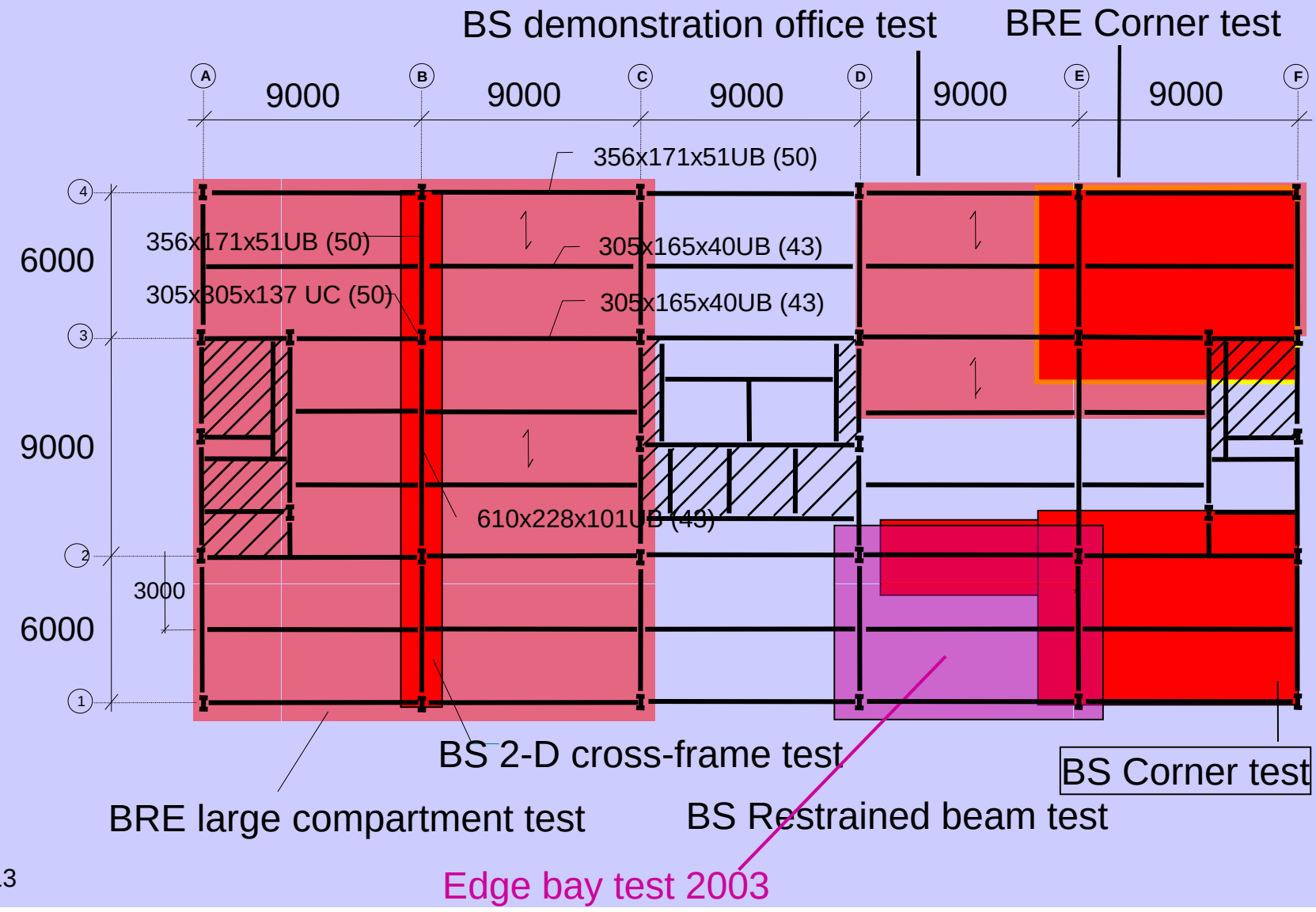




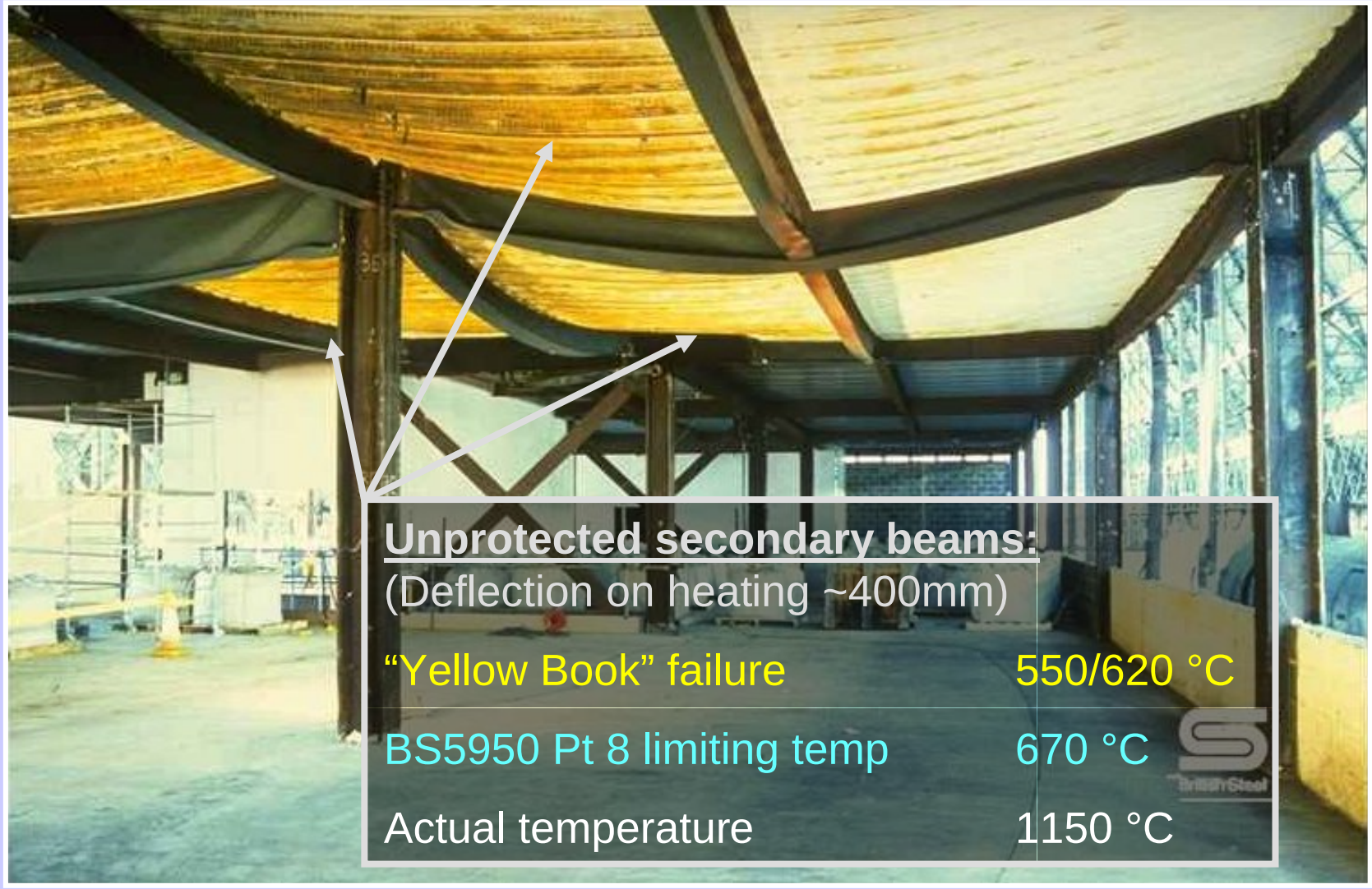
The Cardington composite building



The Cardington test building: floor plan



BS demonstration fire test

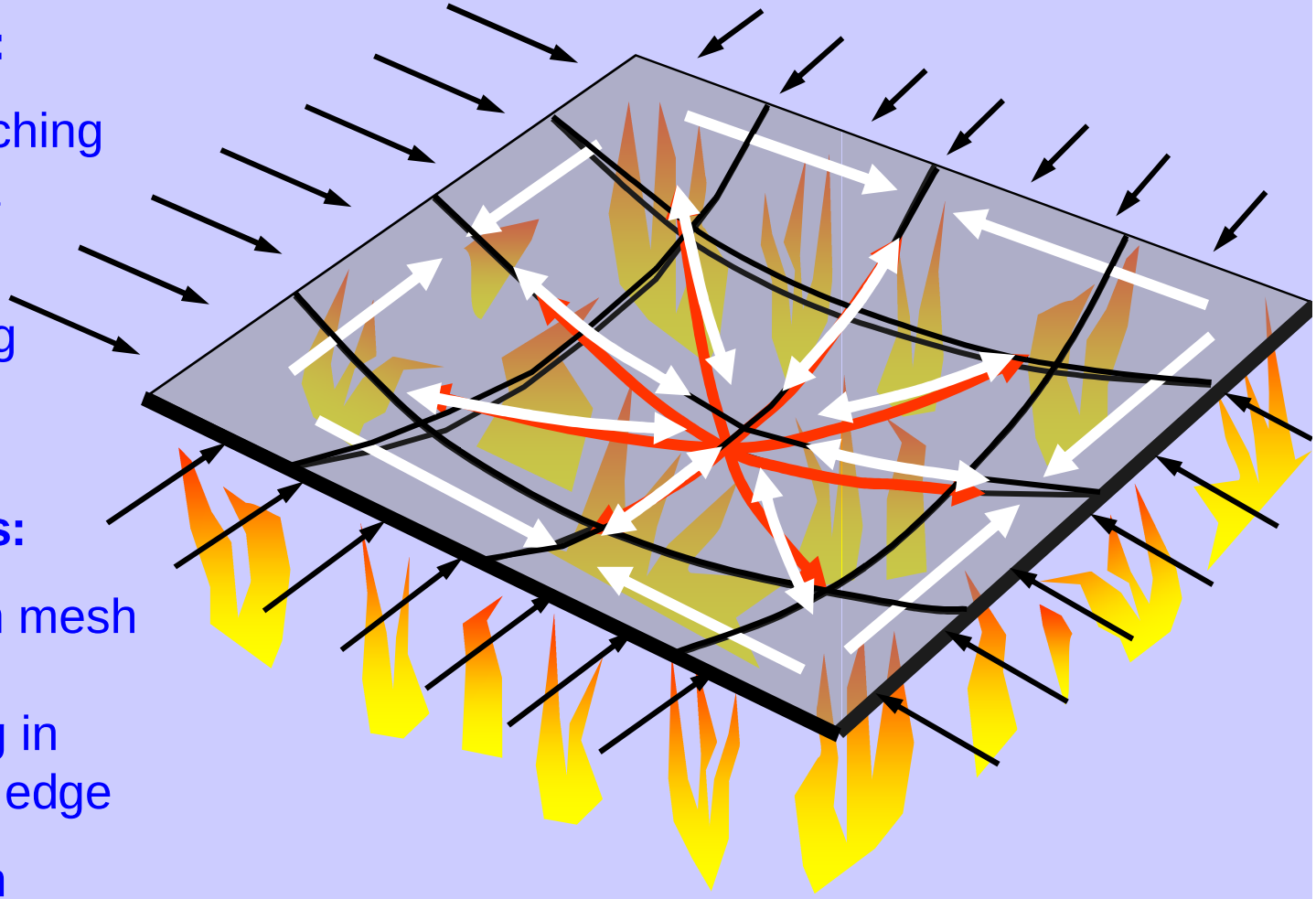


Why did unprotected beams survive to double the conventional critical temperatures ?

Geometrically non-linear actions in slabs

At low deflections:

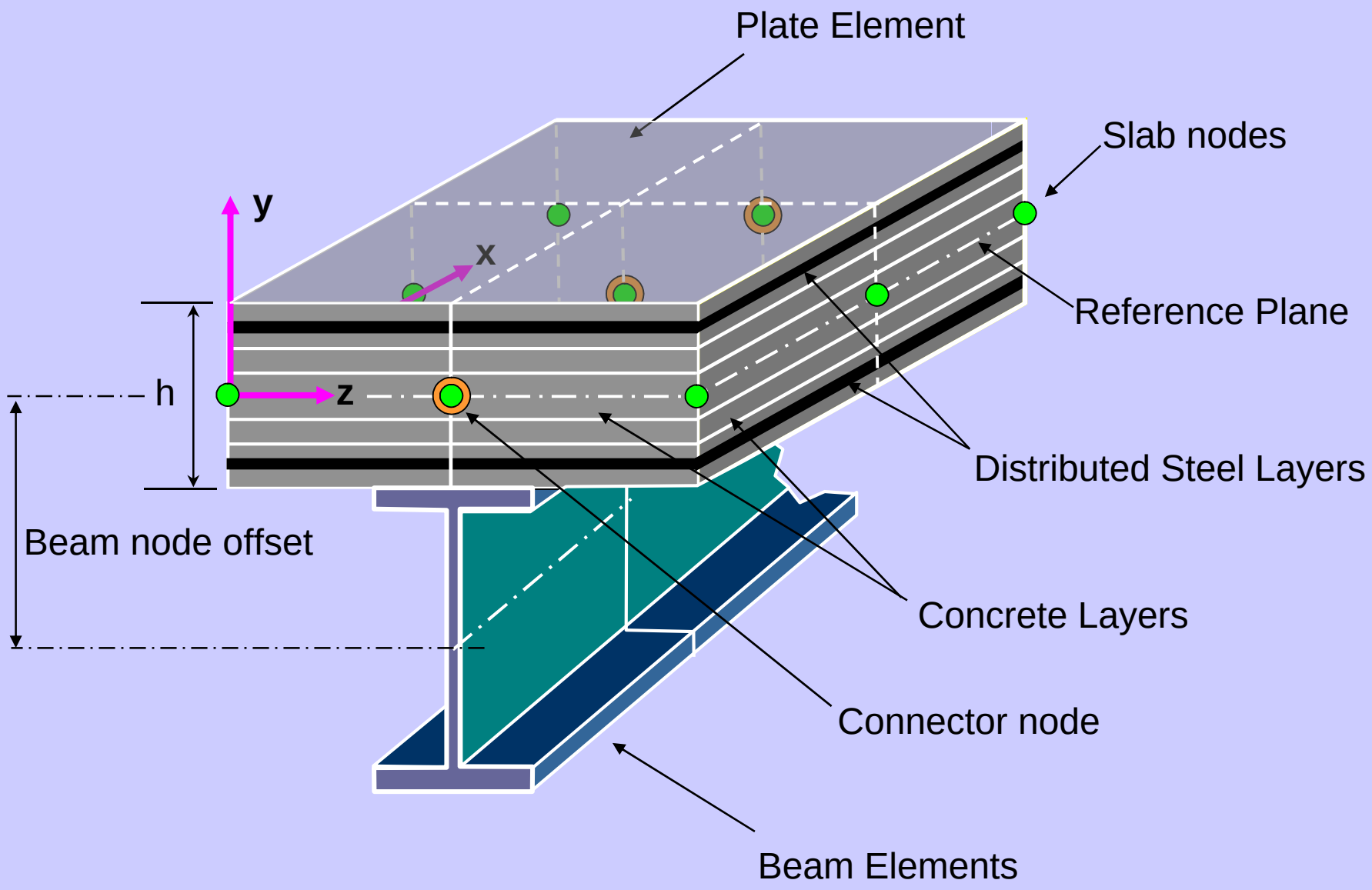
- Compressive arching against adjacent structure
- Thermal buckling



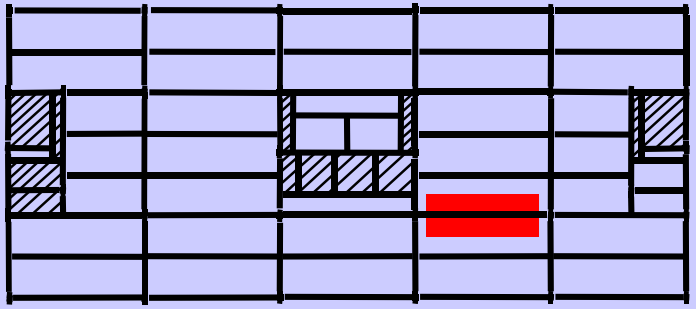
At high deflections:

- Biaxial tension in mesh at centre of slab; compressive ring in concrete around edge
- Catenary tension support, reacting against adjacent structure

Finite Element Principles of Vulcan



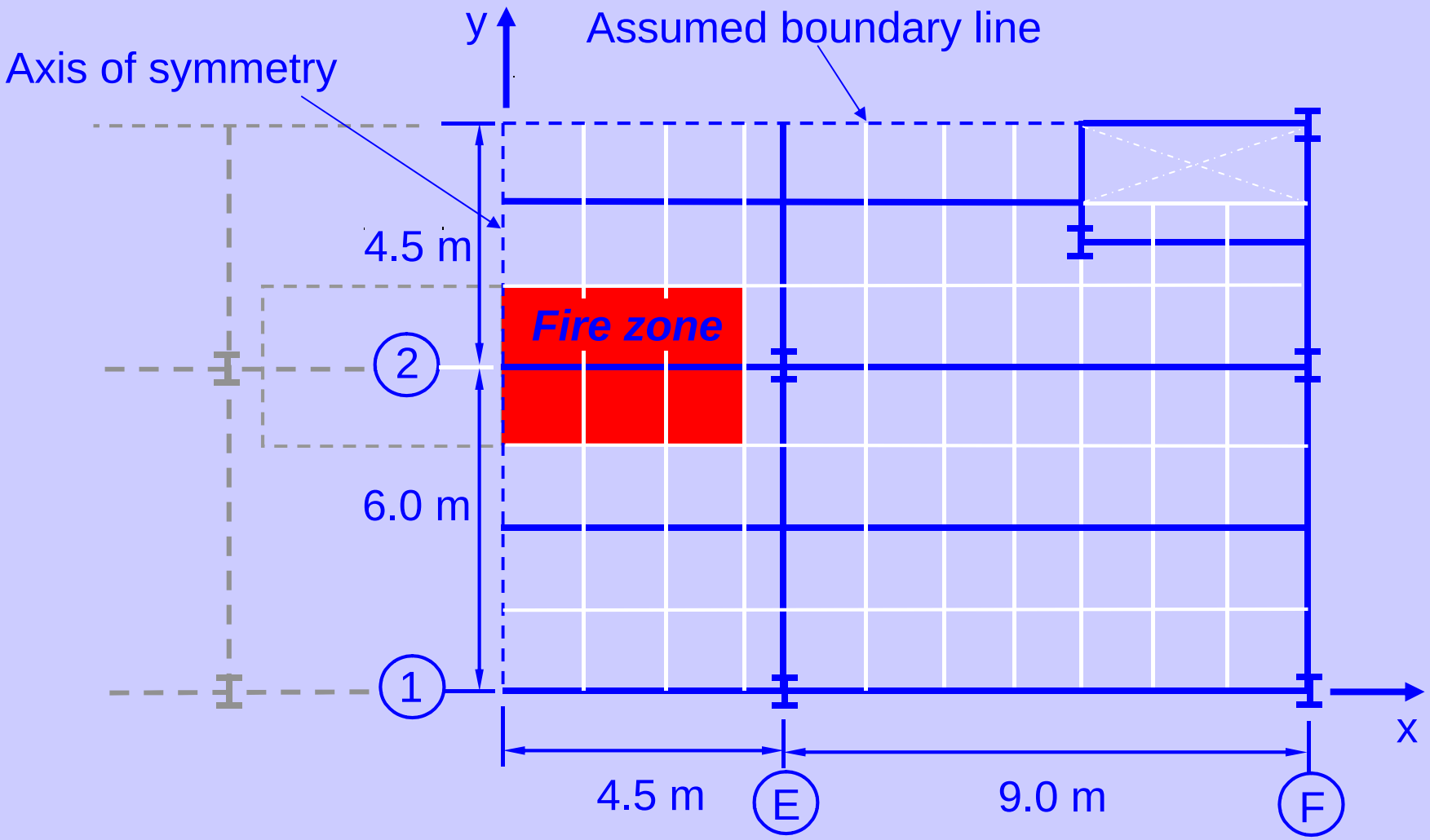
The Restrained Beam Test



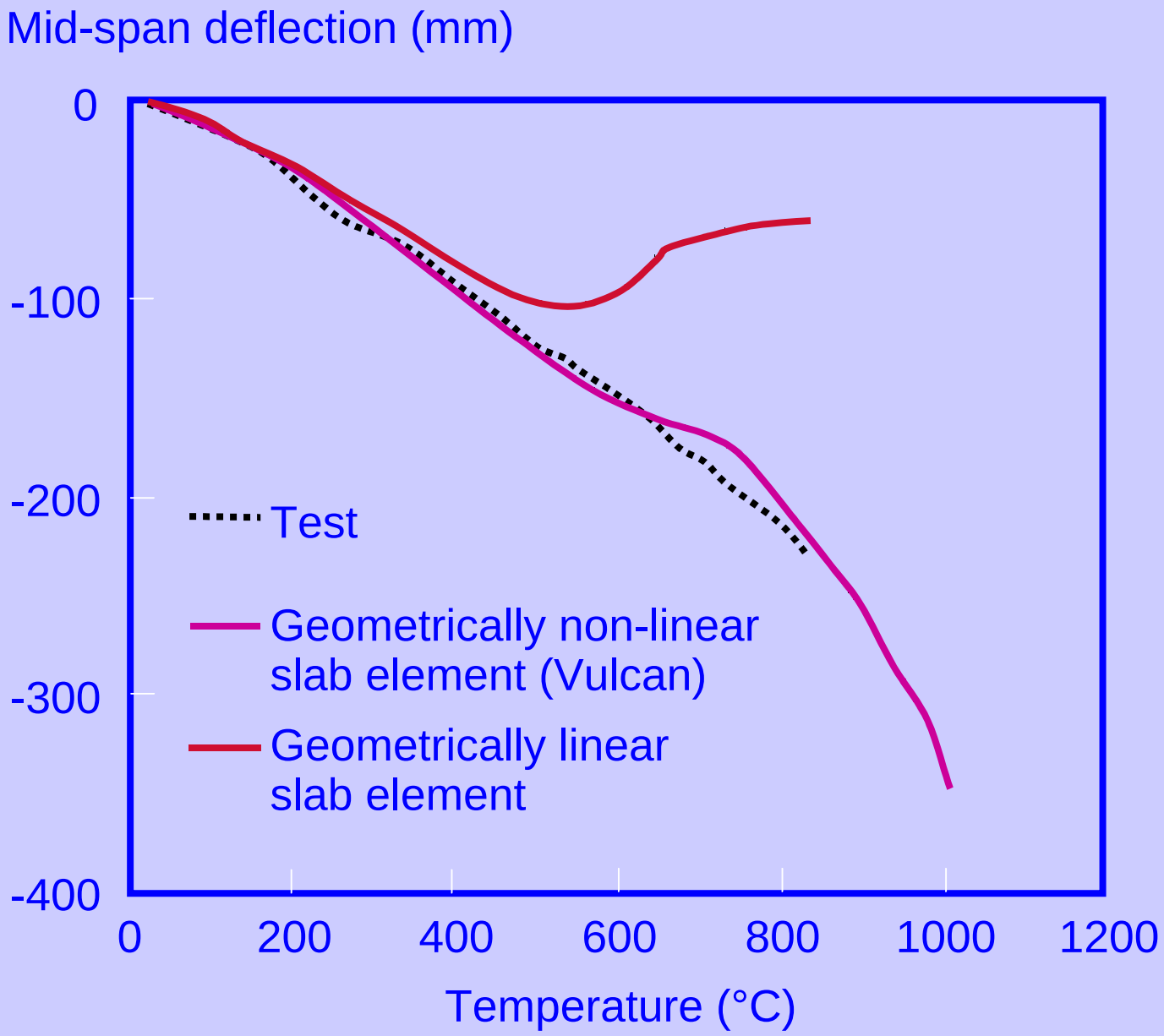
BS Restrained beam test
8m heated

- Steel temperature 834°C
- Slab temperature 481°C
- Deflection ≈ span/40
- Test terminated due to very slow heating rate

Restrained Beam Test: analysis

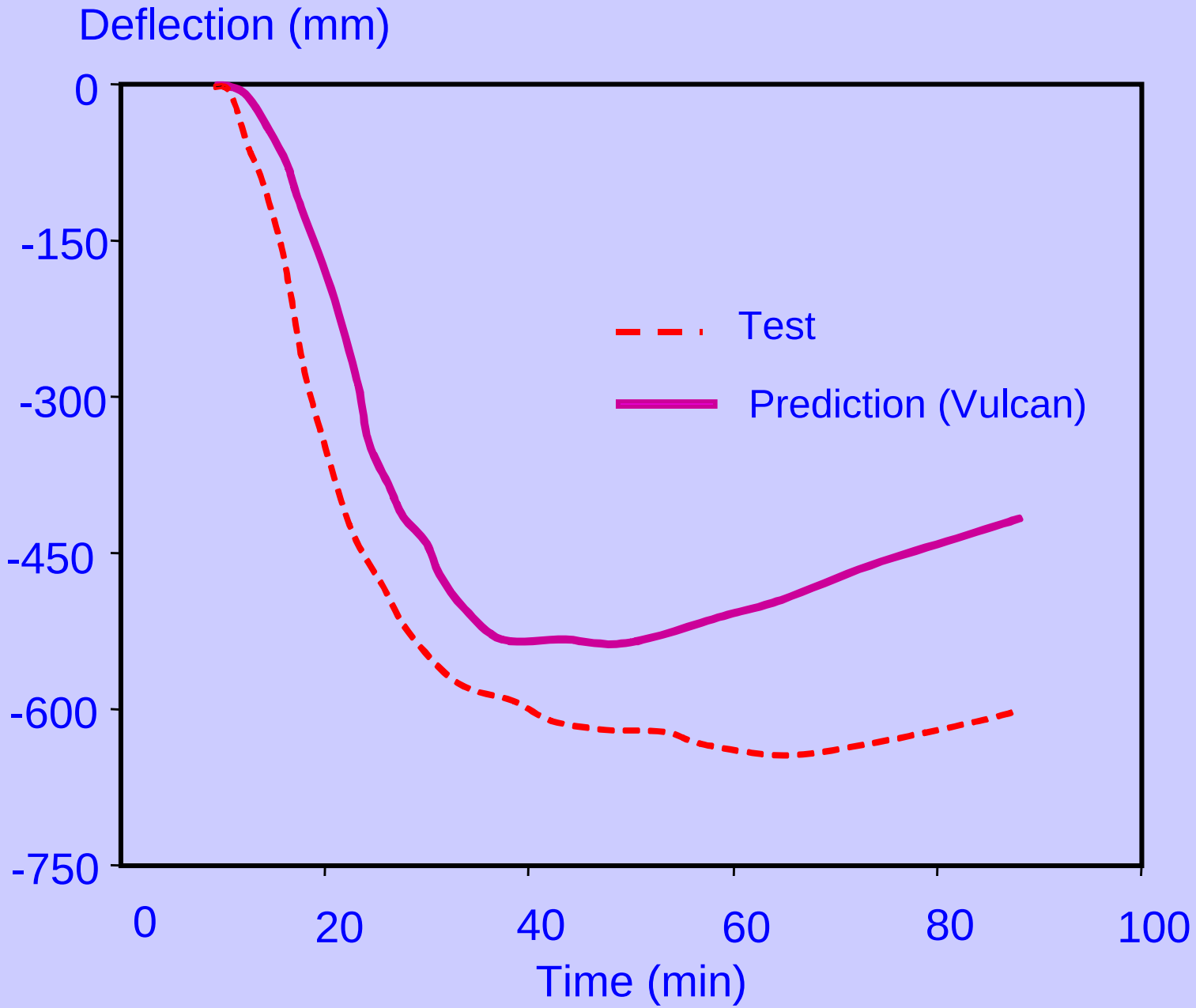


Restrained Beam: deflections

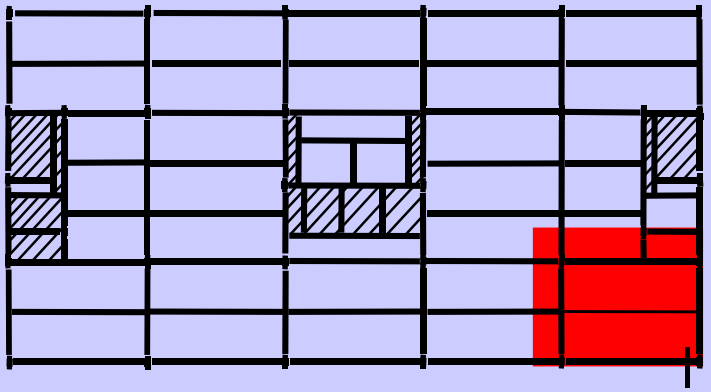


BS demonstration test: fire load

British Steel demonstration test



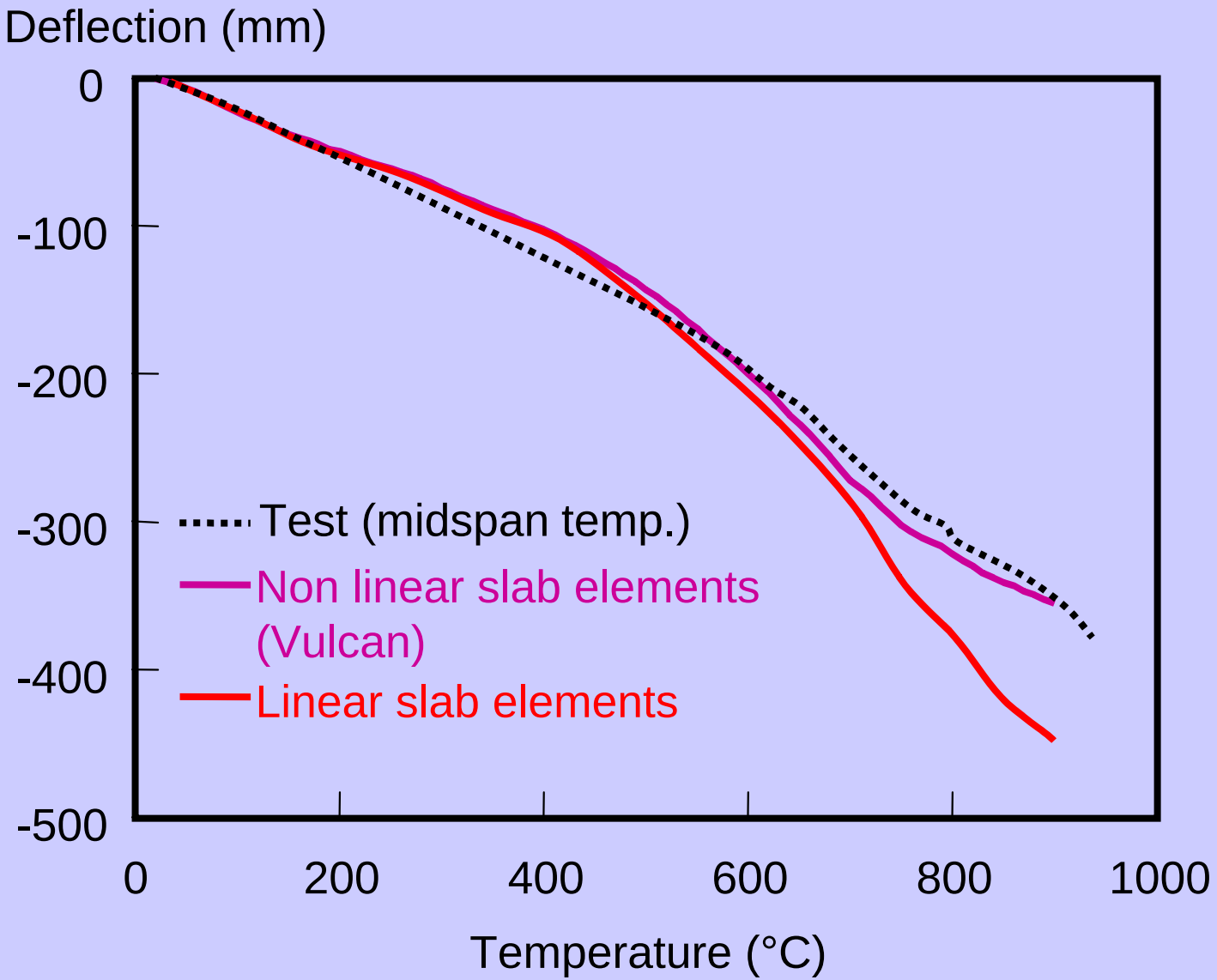
The British Steel Corner Bay Test



BS Corner test

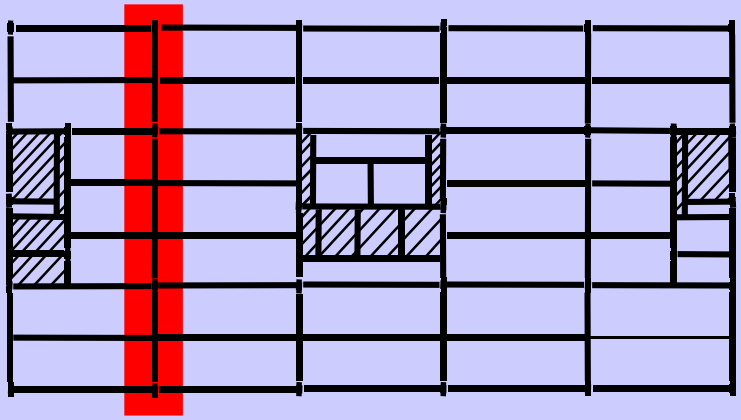
- Fire: 45kg/m^2 of timber
- Max. fire temperature 1028°C at 80 minutes
- Max. steel temp >900°C
- Max. slab temperatures 360°C (bottom) and 70°C (top)

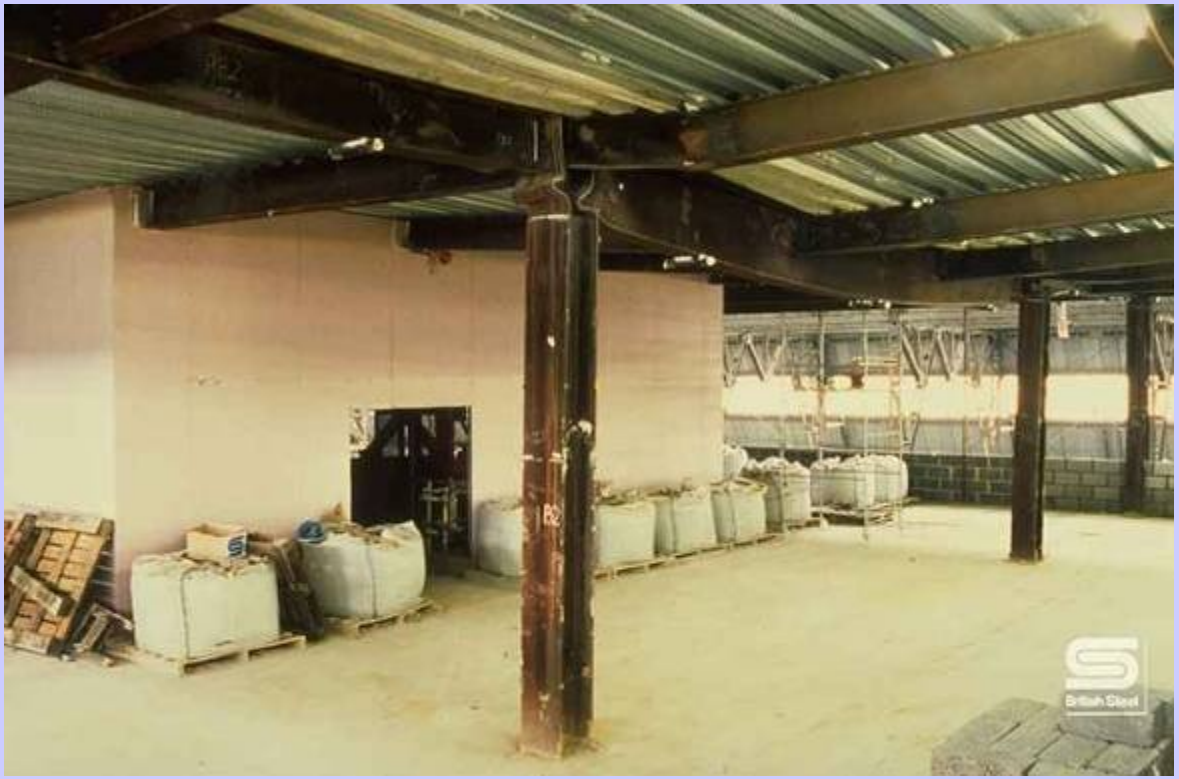
British Steel Corner Test - deflections



Plane frame test

- Gas furnace across primary frame
- Max. steel temperature (lower flange) 1150°C
- Top 500mm of internal columns unprotected – with very visible results

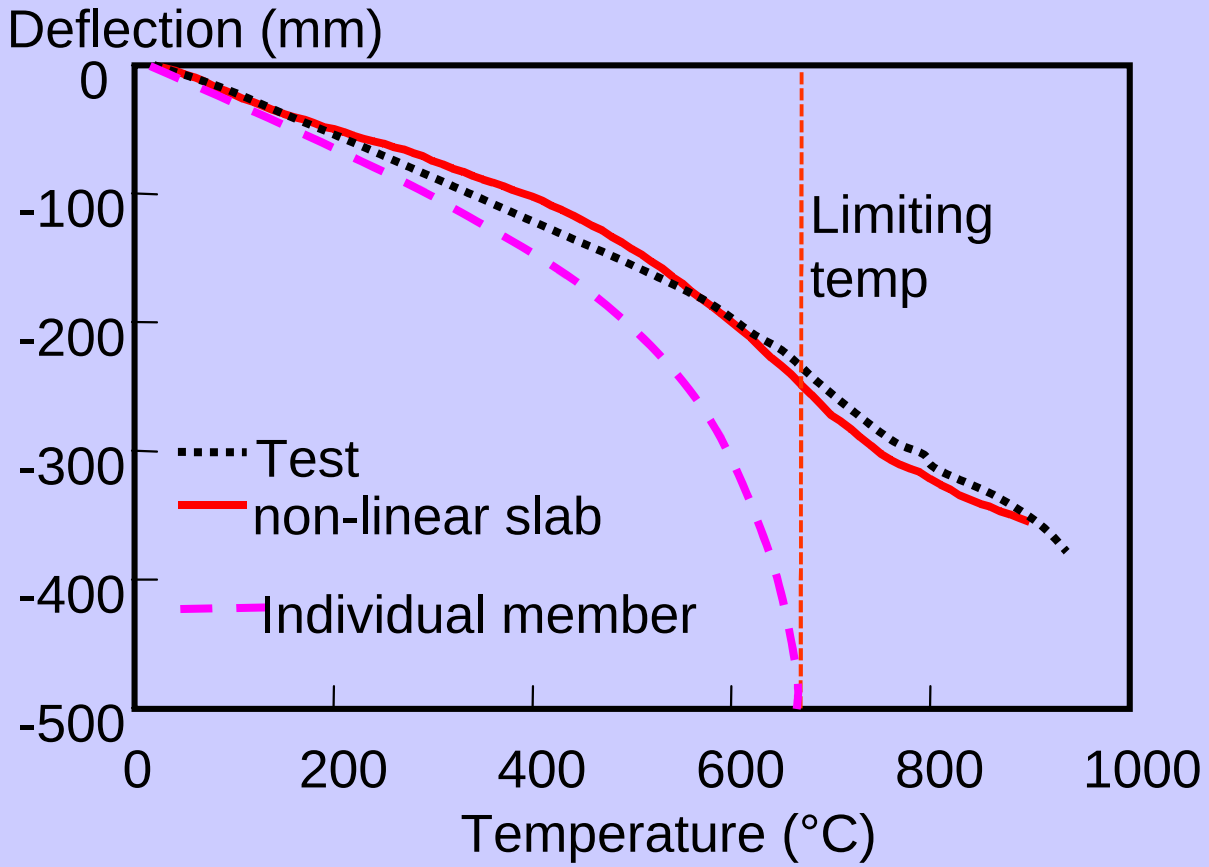




Plane frame test

Summary of Cardington results

- Contribution of slab very important
- Non-linear analytical model validated
- Translation into practice



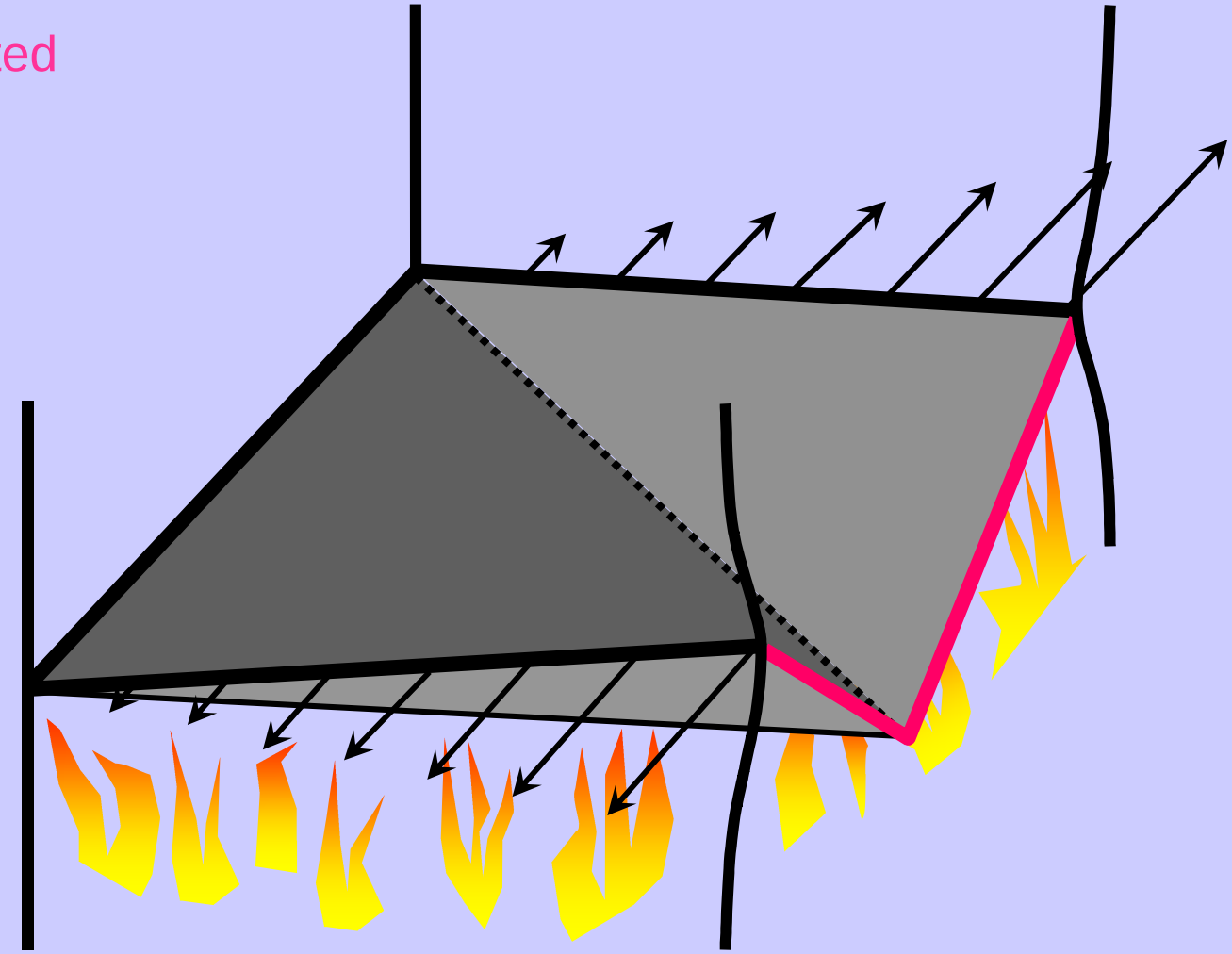
What conditions required for membrane action

- Physical requirements
- Simplified design approaches for non-specialists

Possible catenary action

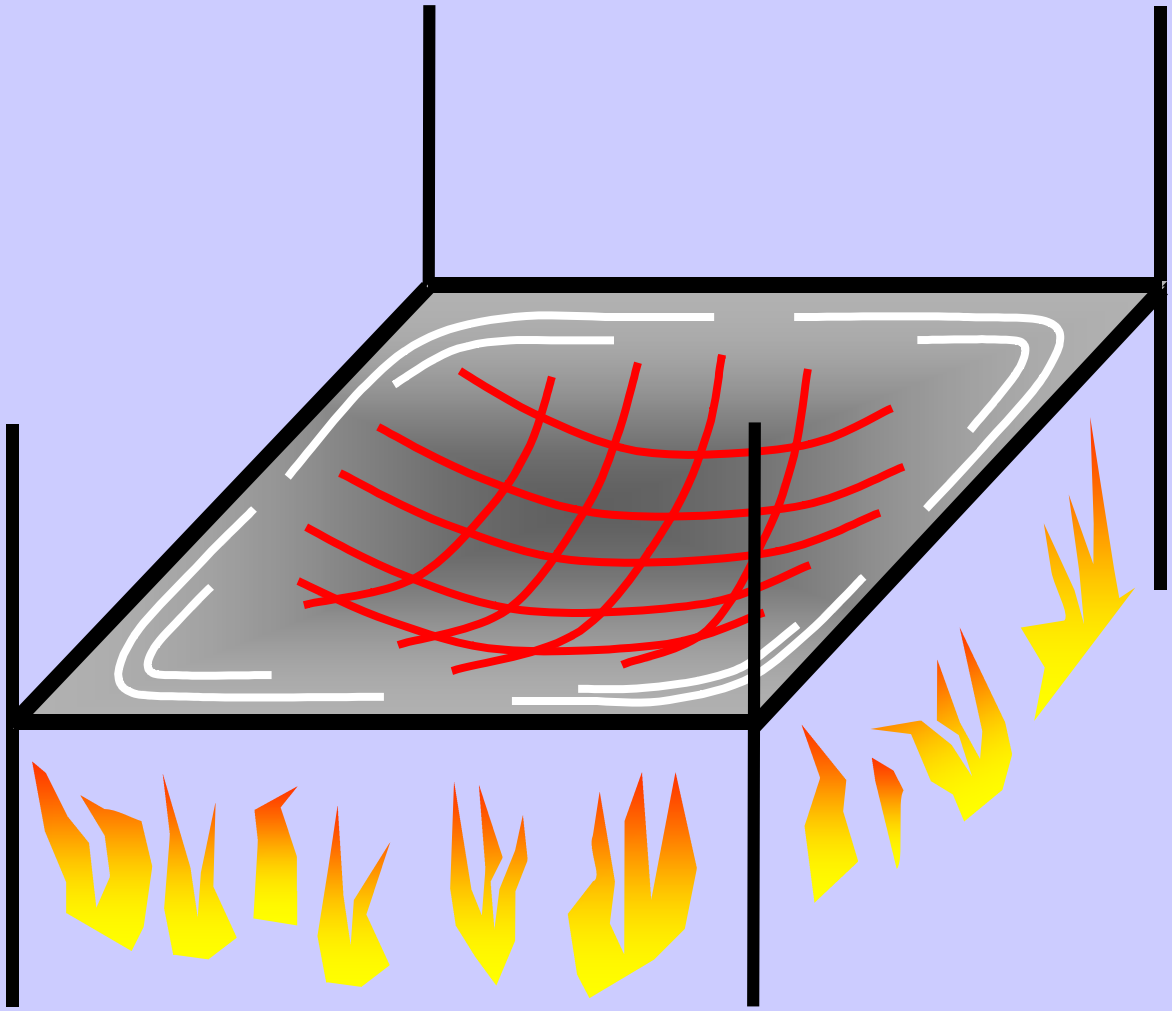
Protected

Unprotected



Tensile membrane action

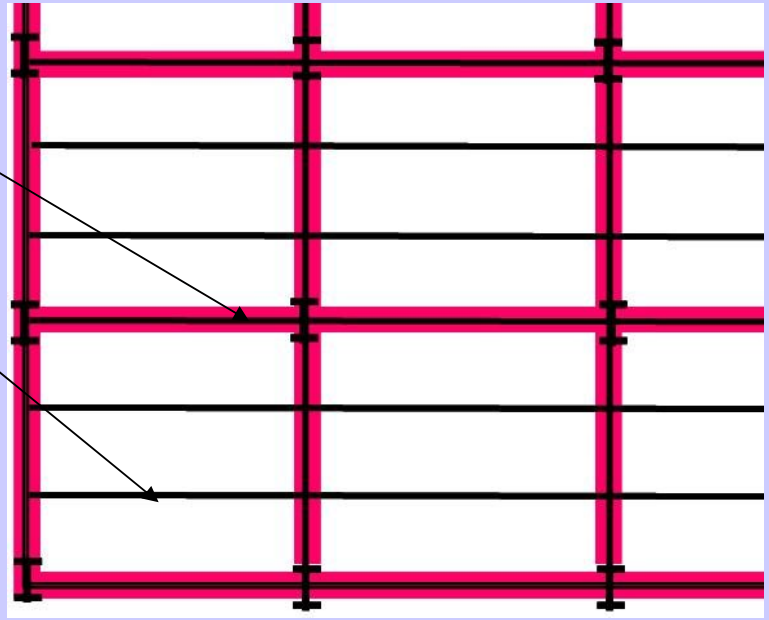
Protected



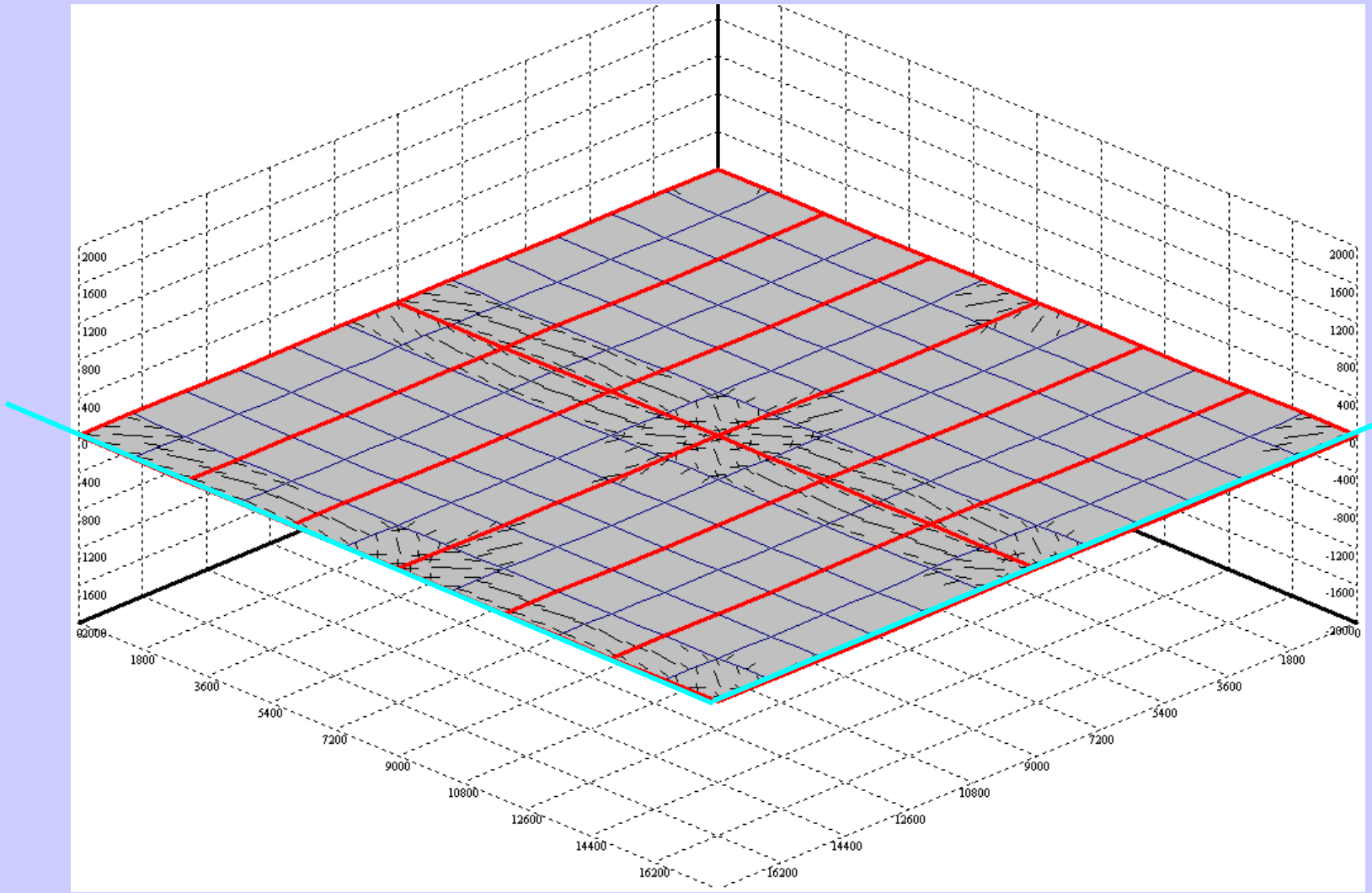
Vertical support required on all 4 edges to enable tensile membrane action to develop

Typical Design Strategy

- Provide edge support to individual bays
  - Protect columns on column gridlines
  - Leave intermediate beams unprotected
- Consider tensile membrane action between protected members
- FE analysis (*Vulcan*) or simplified design approaches

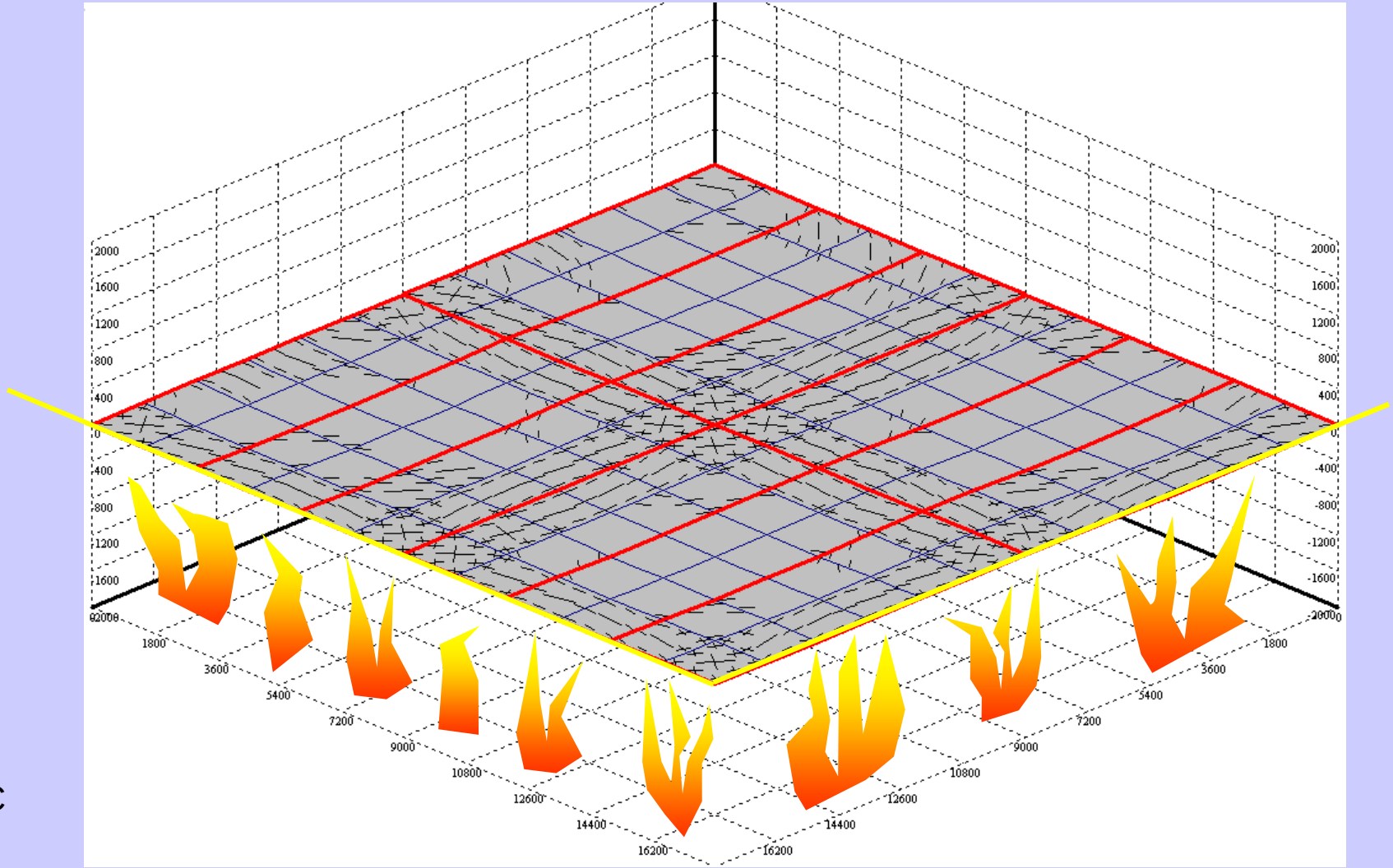


Example: Deflected shapes



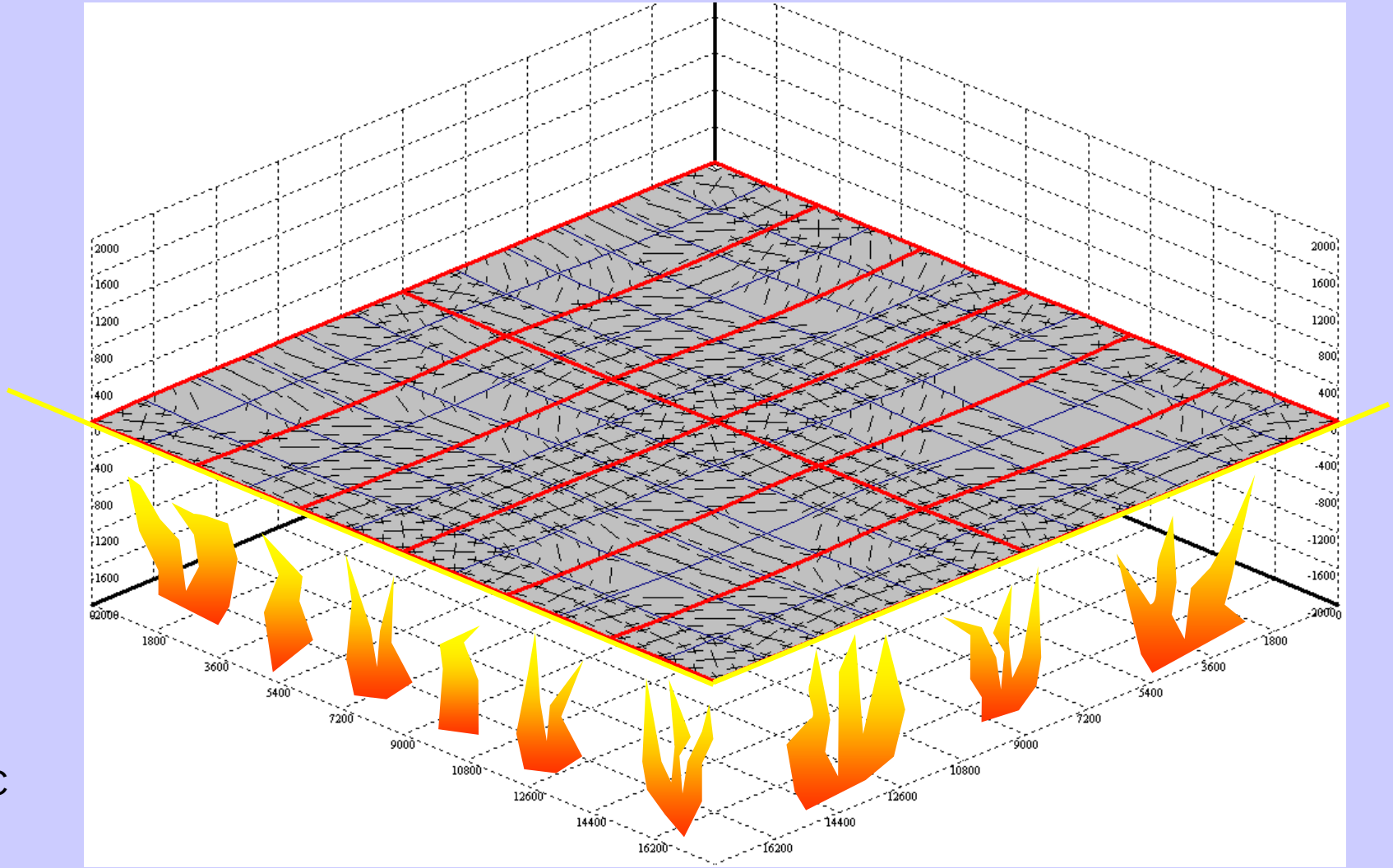
20°C

Example: Deflected shapes



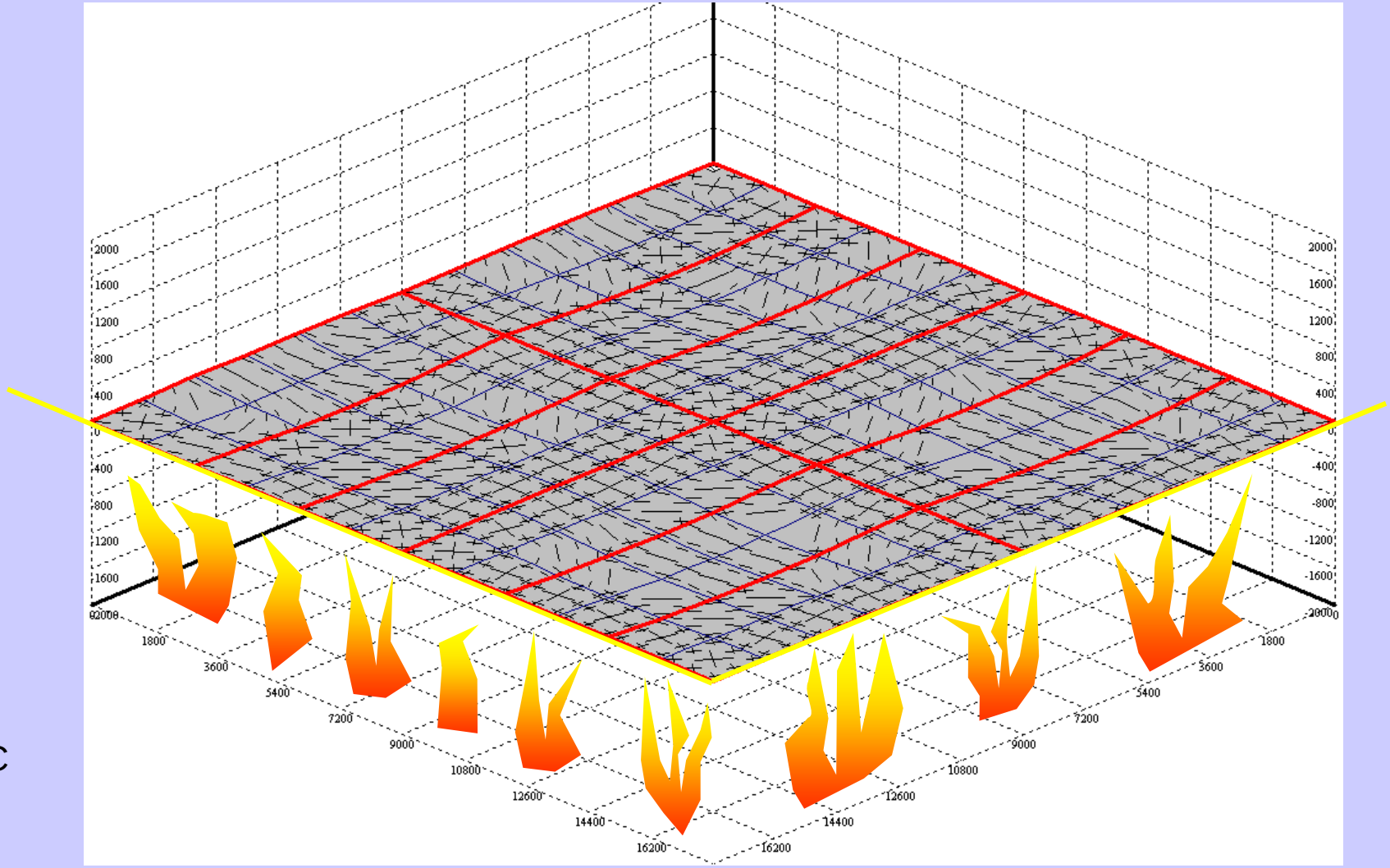
100°C

Example: Deflected shapes



200°C

Example: Deflected shapes



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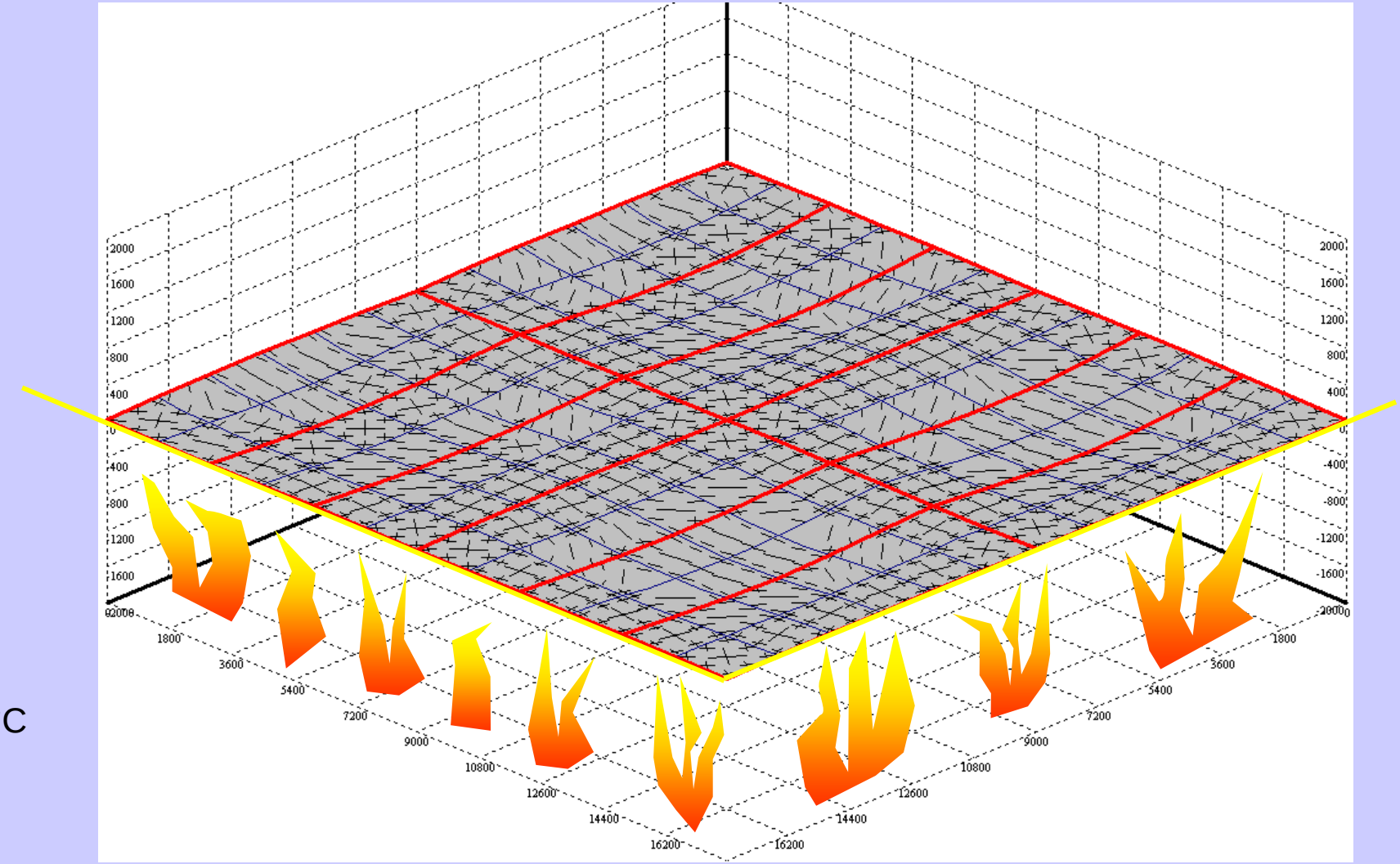
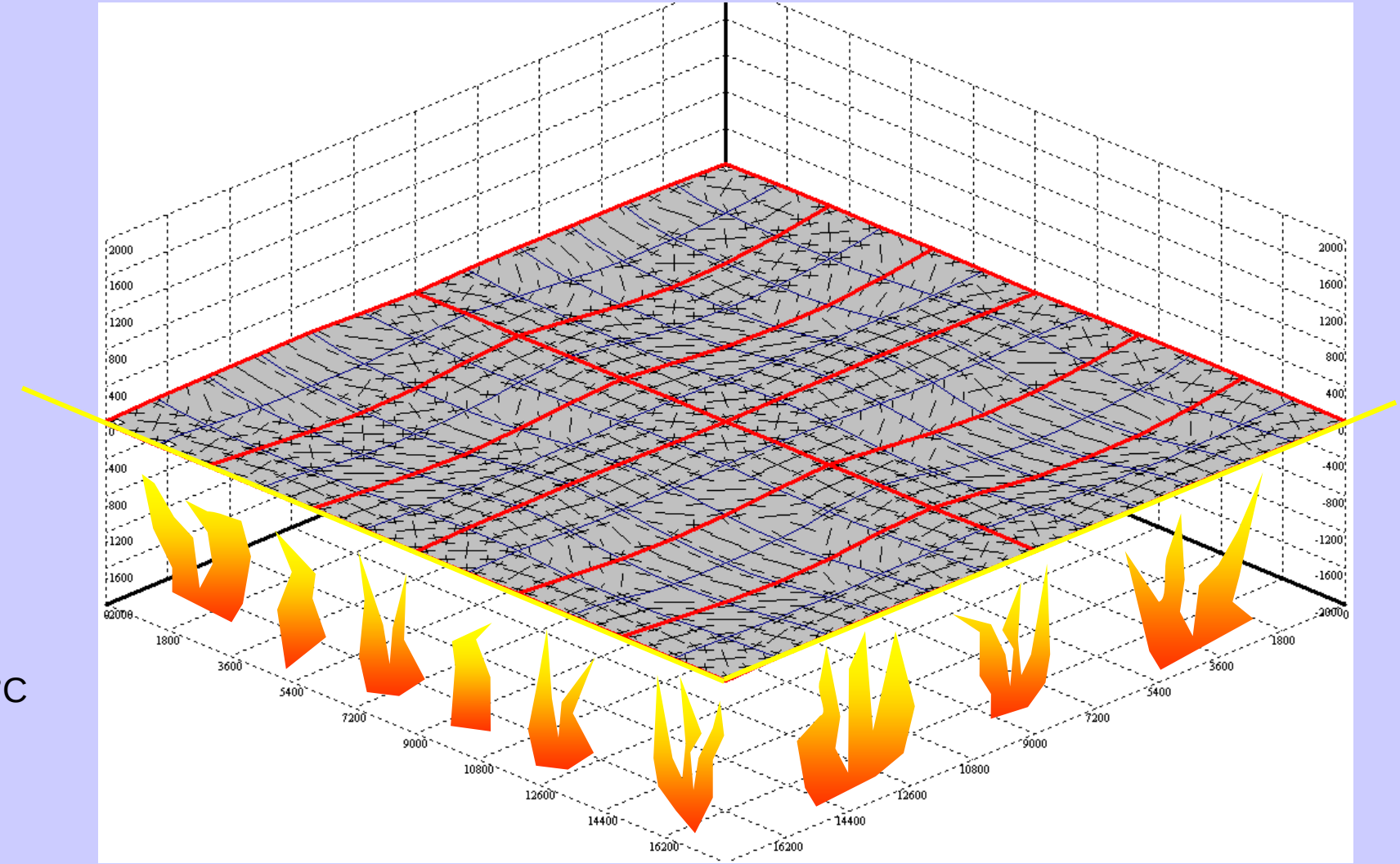


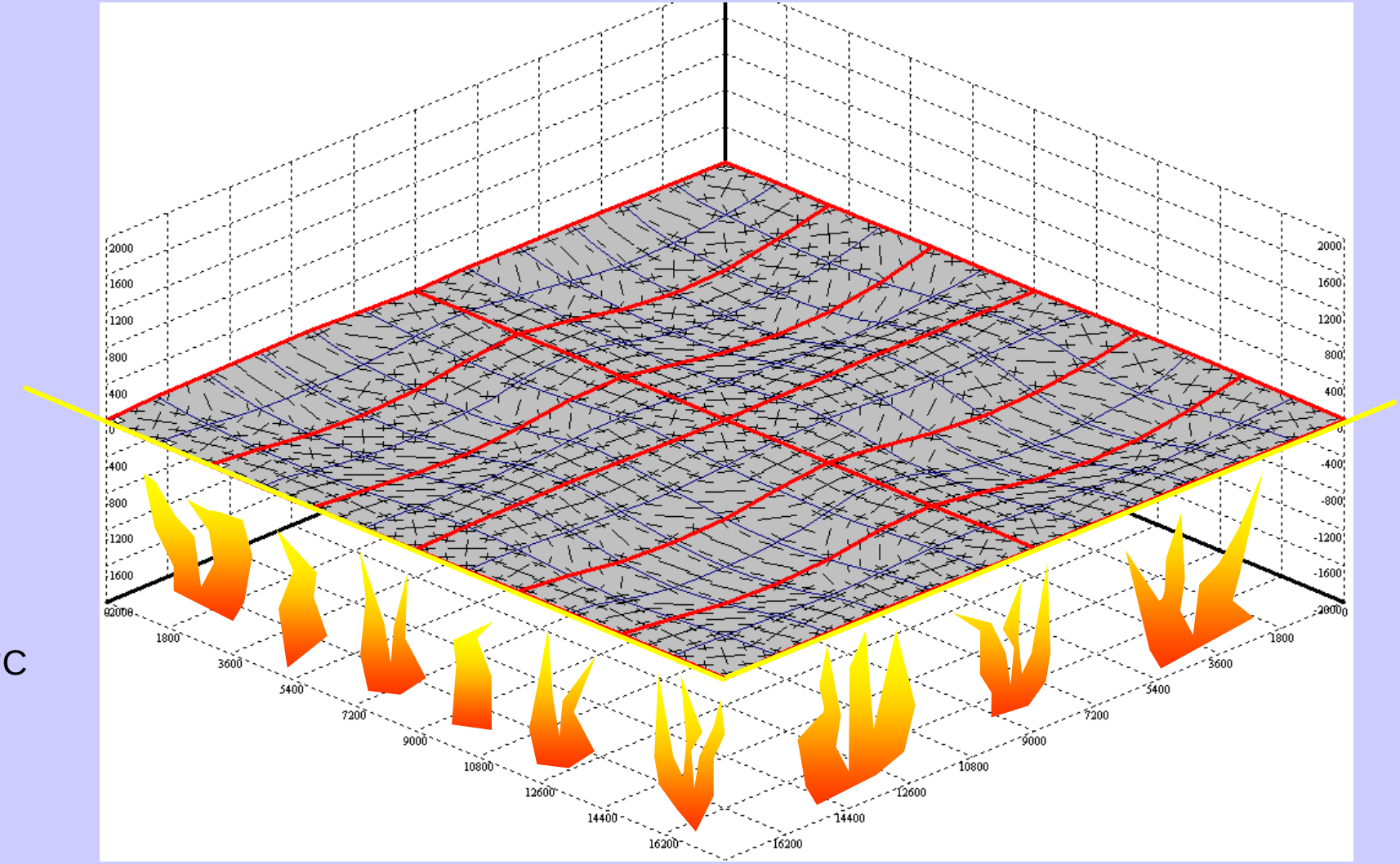
400°C

Example: Deflected shapes

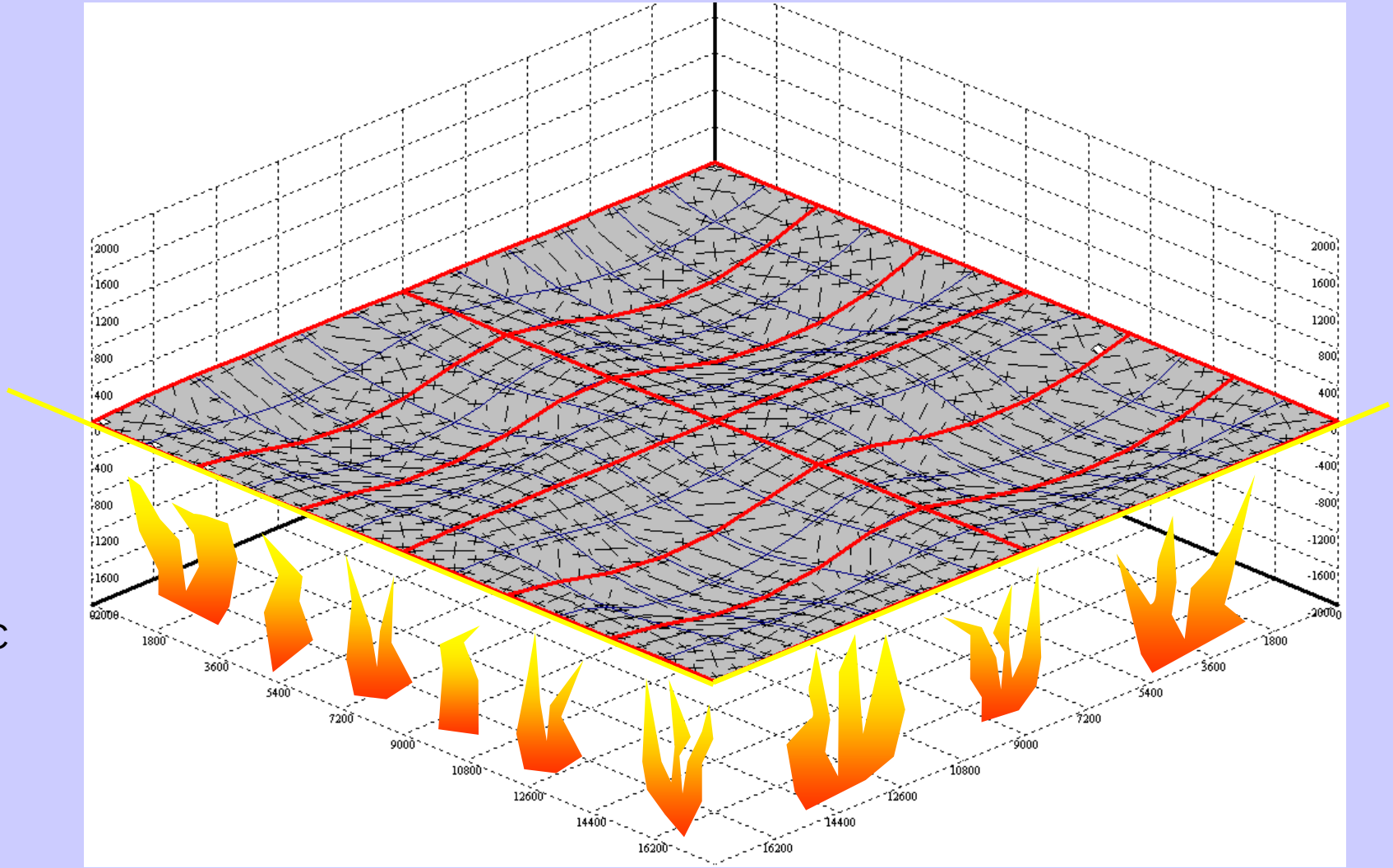


500°C

Example: Deflected shapes

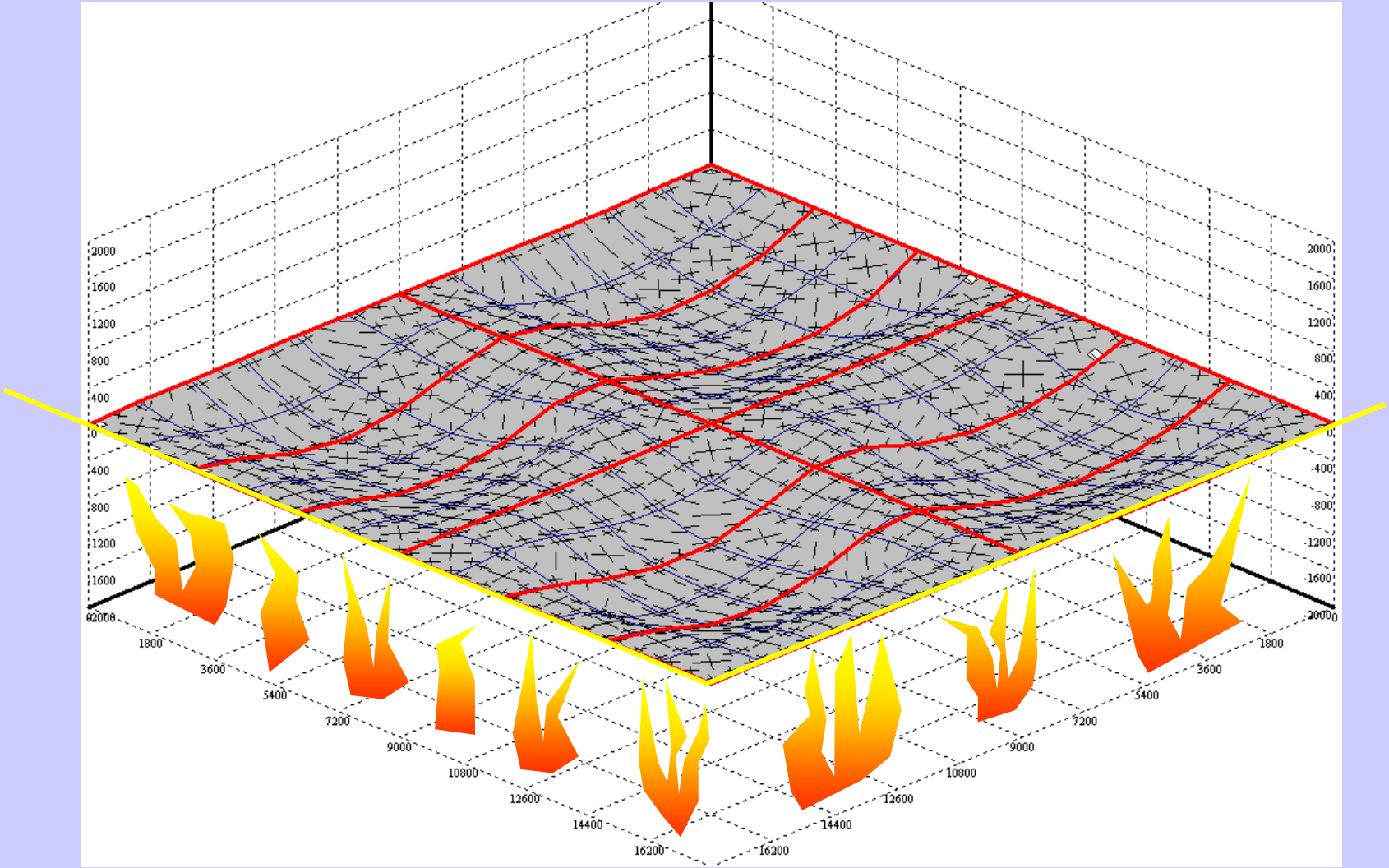


Example: Deflected shapes



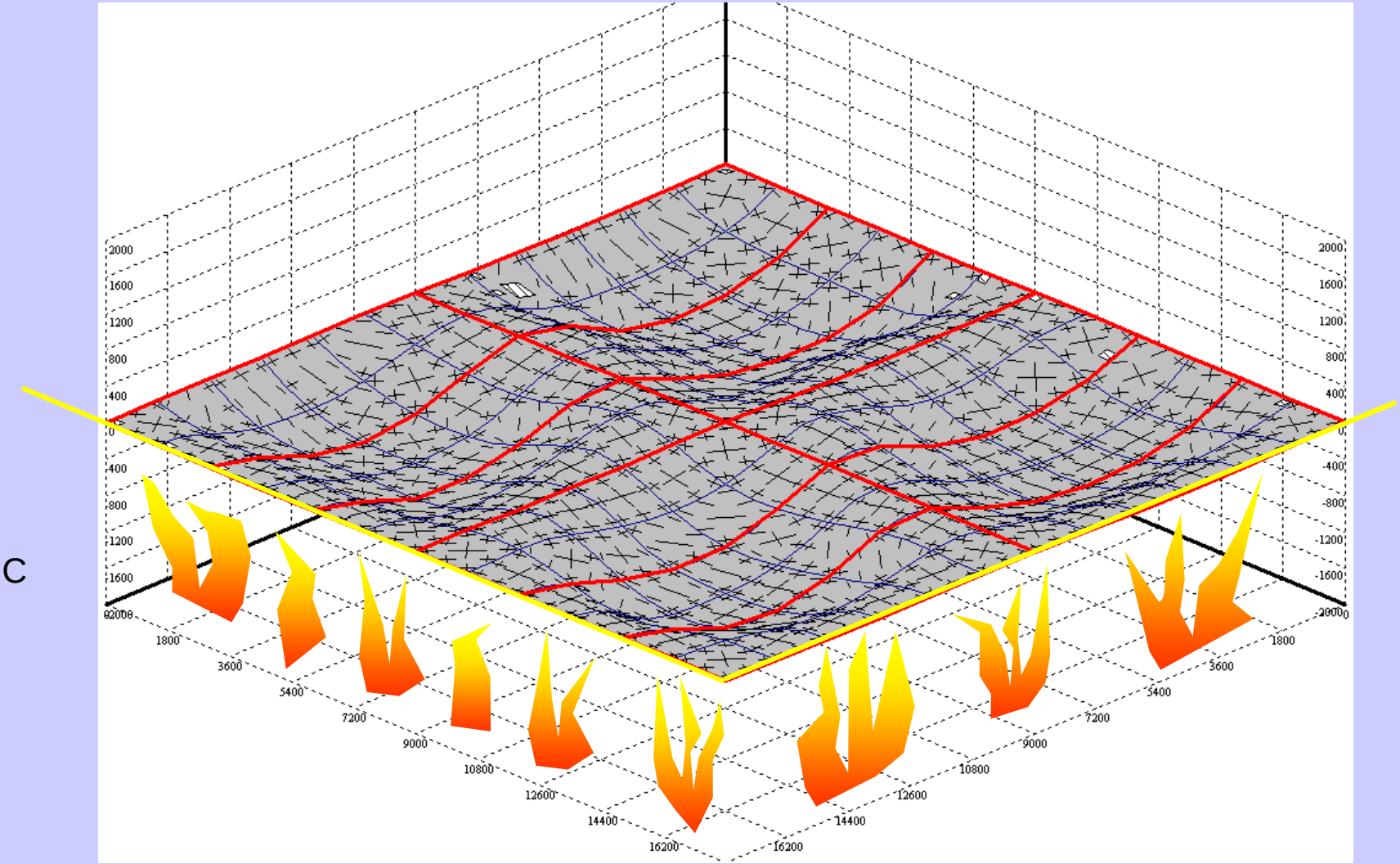
700°C

Example: Deflected shapes



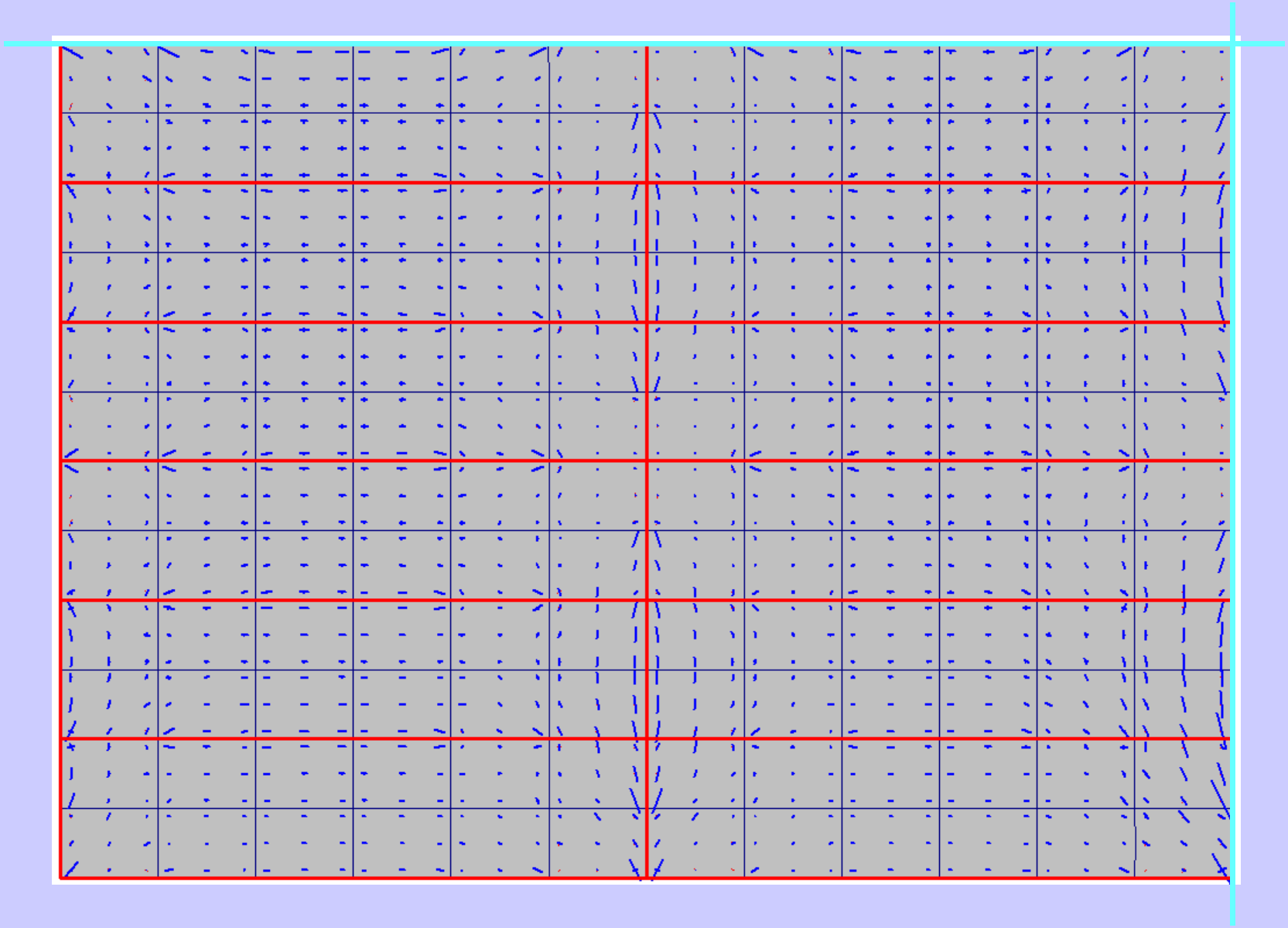
800°C

Example: Deflected shapes



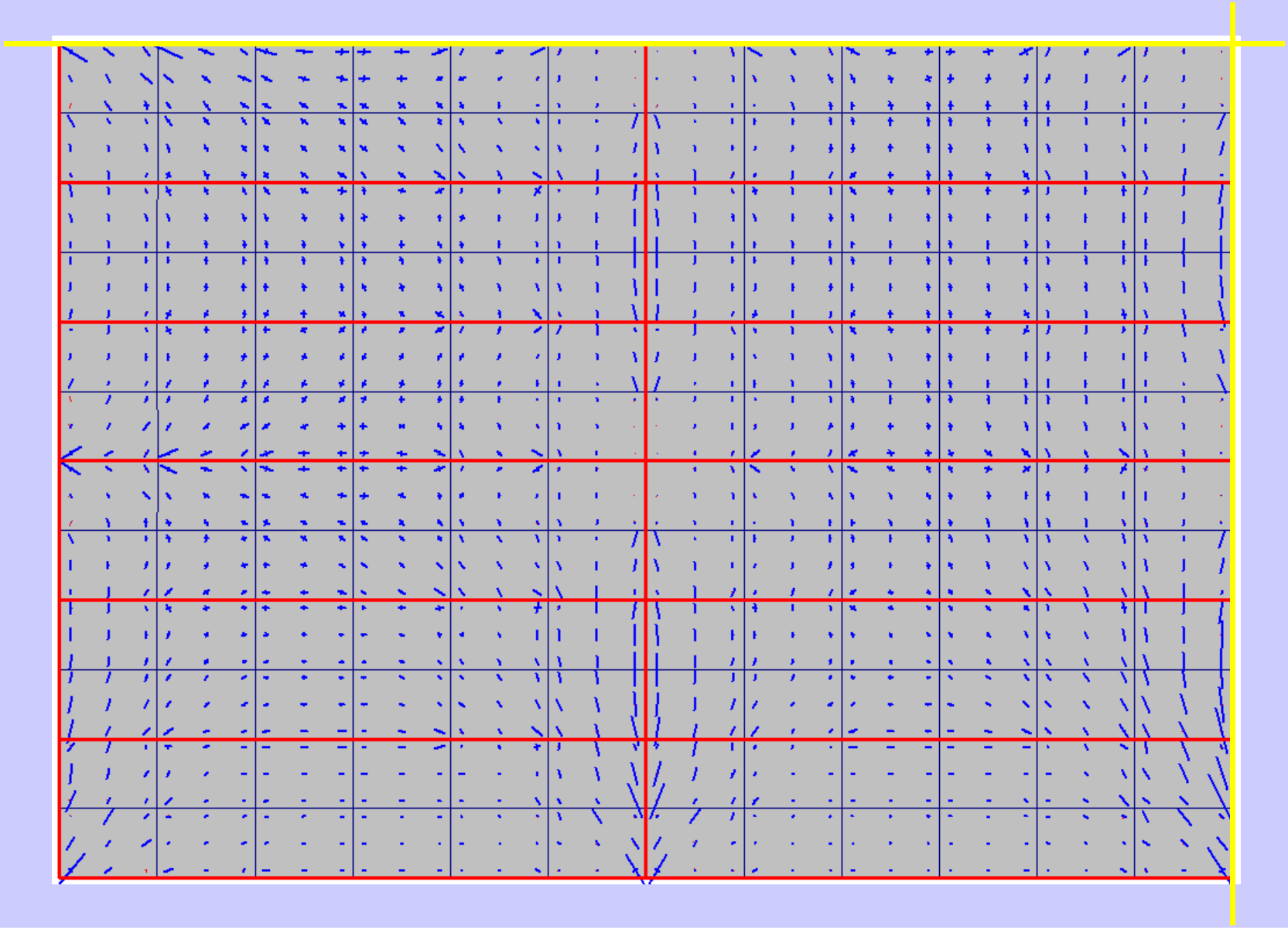
900°C

Example: Principal membrane tractions



20°C

Example: Principal membrane tractions



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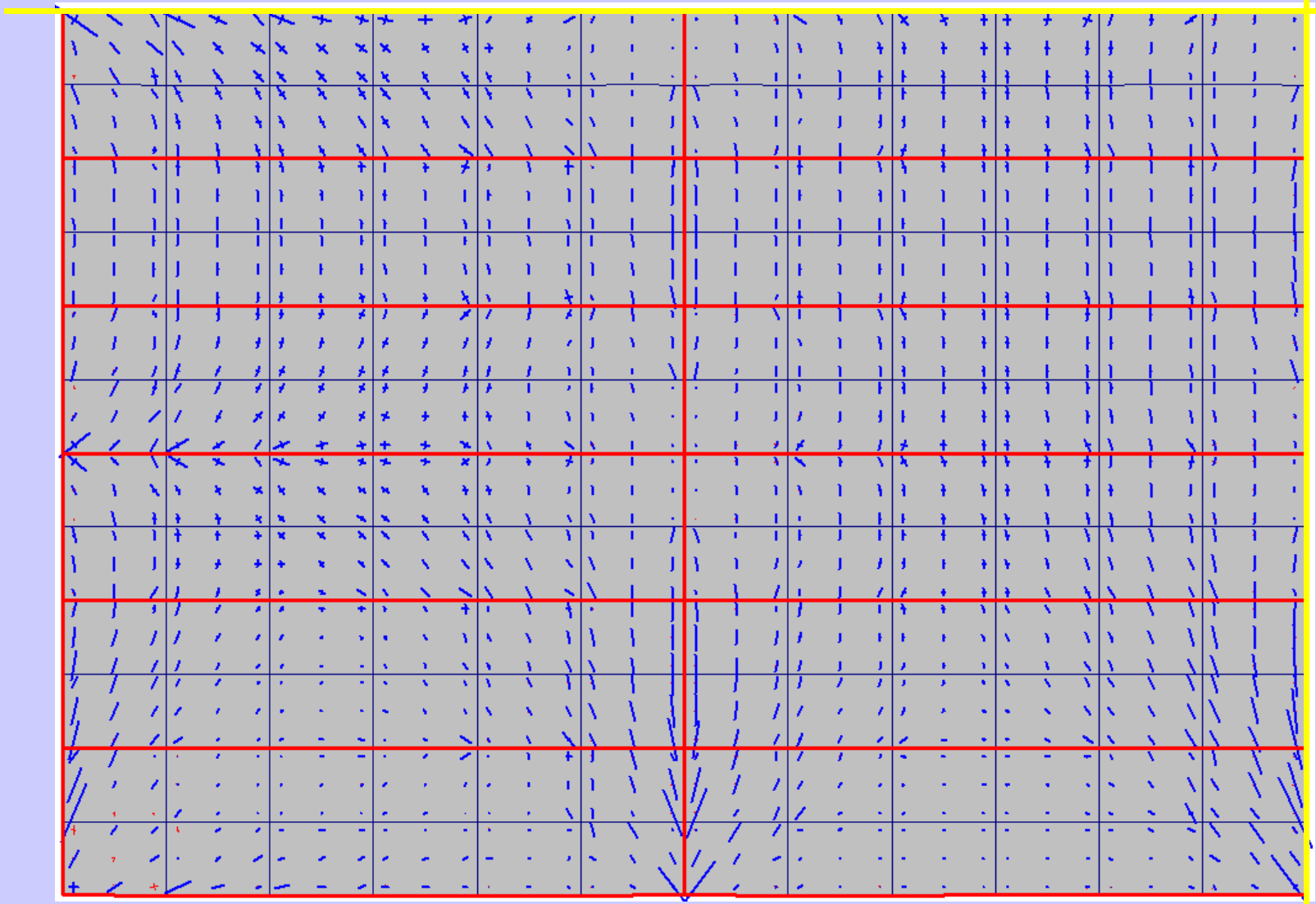
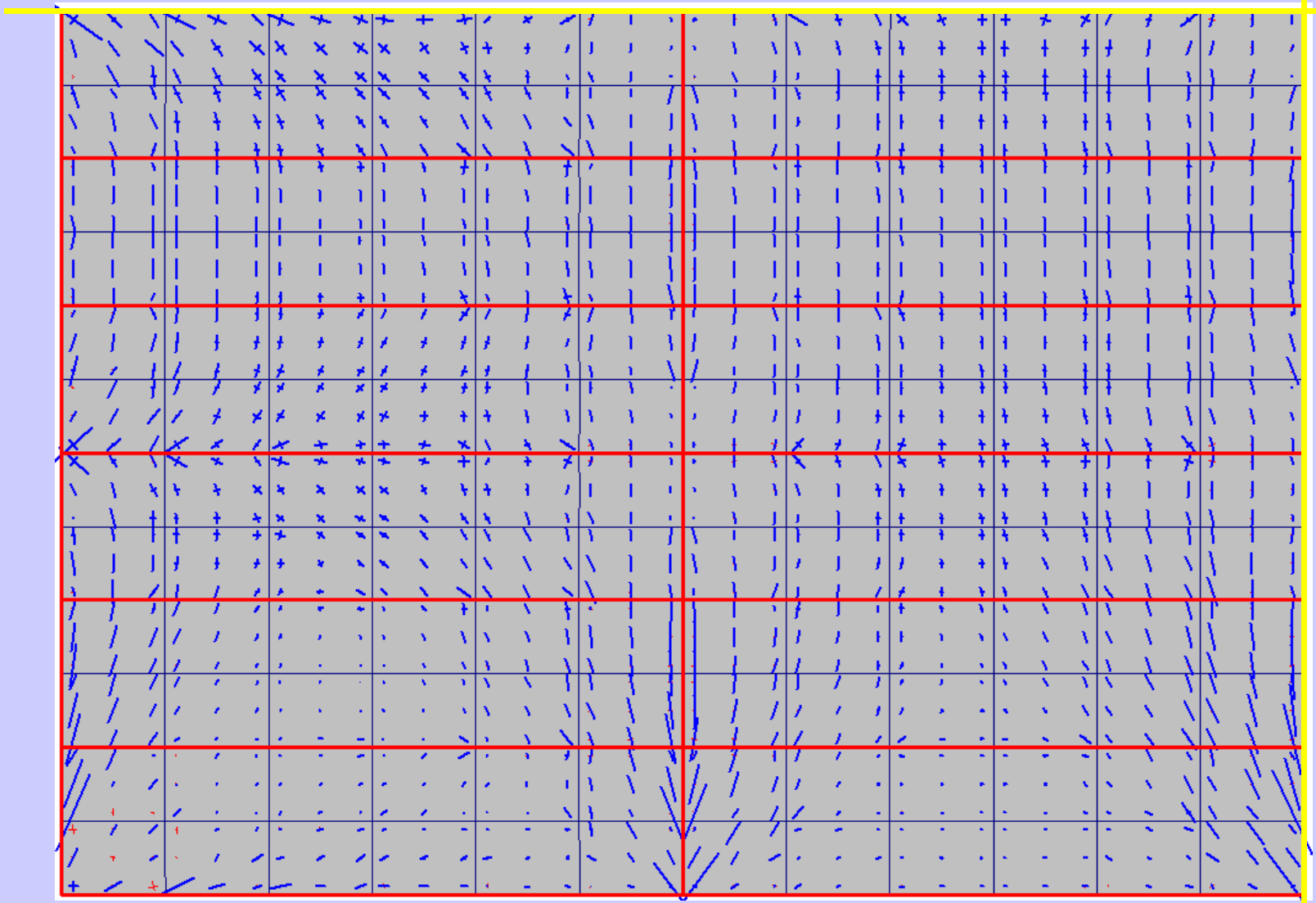


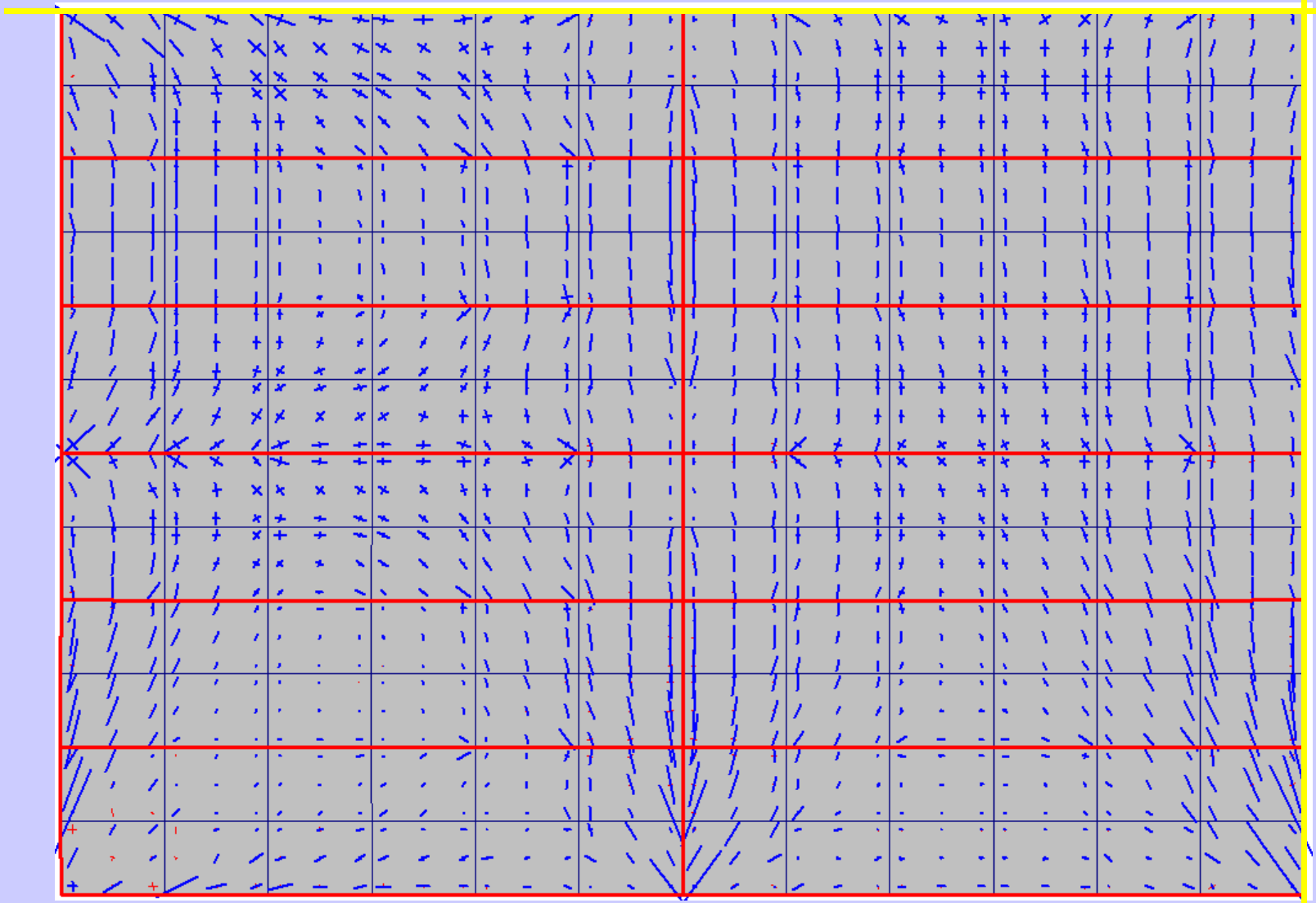
200°C

Example: Principal membrane tractions



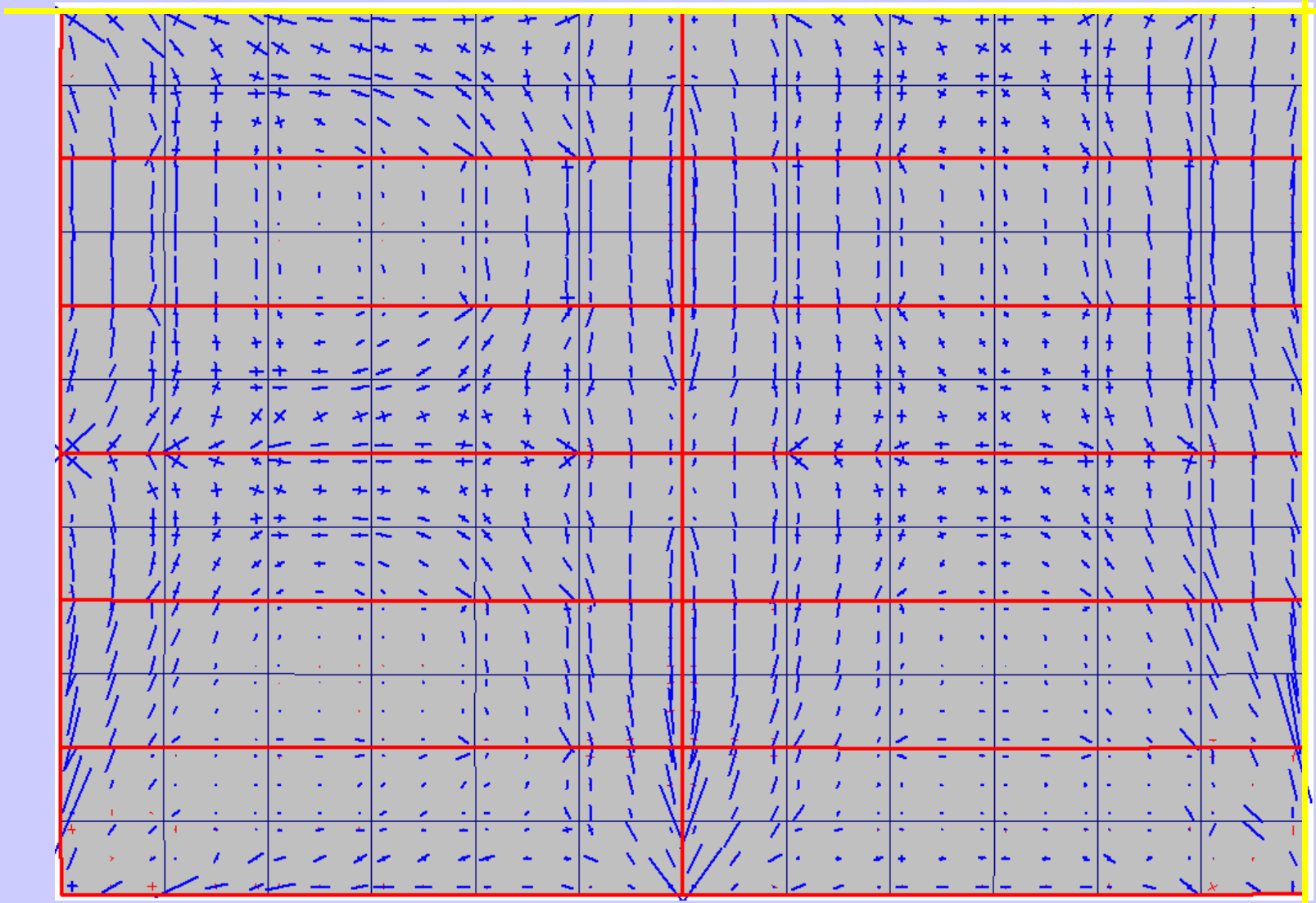
300°C

Example: Principal membrane tractions



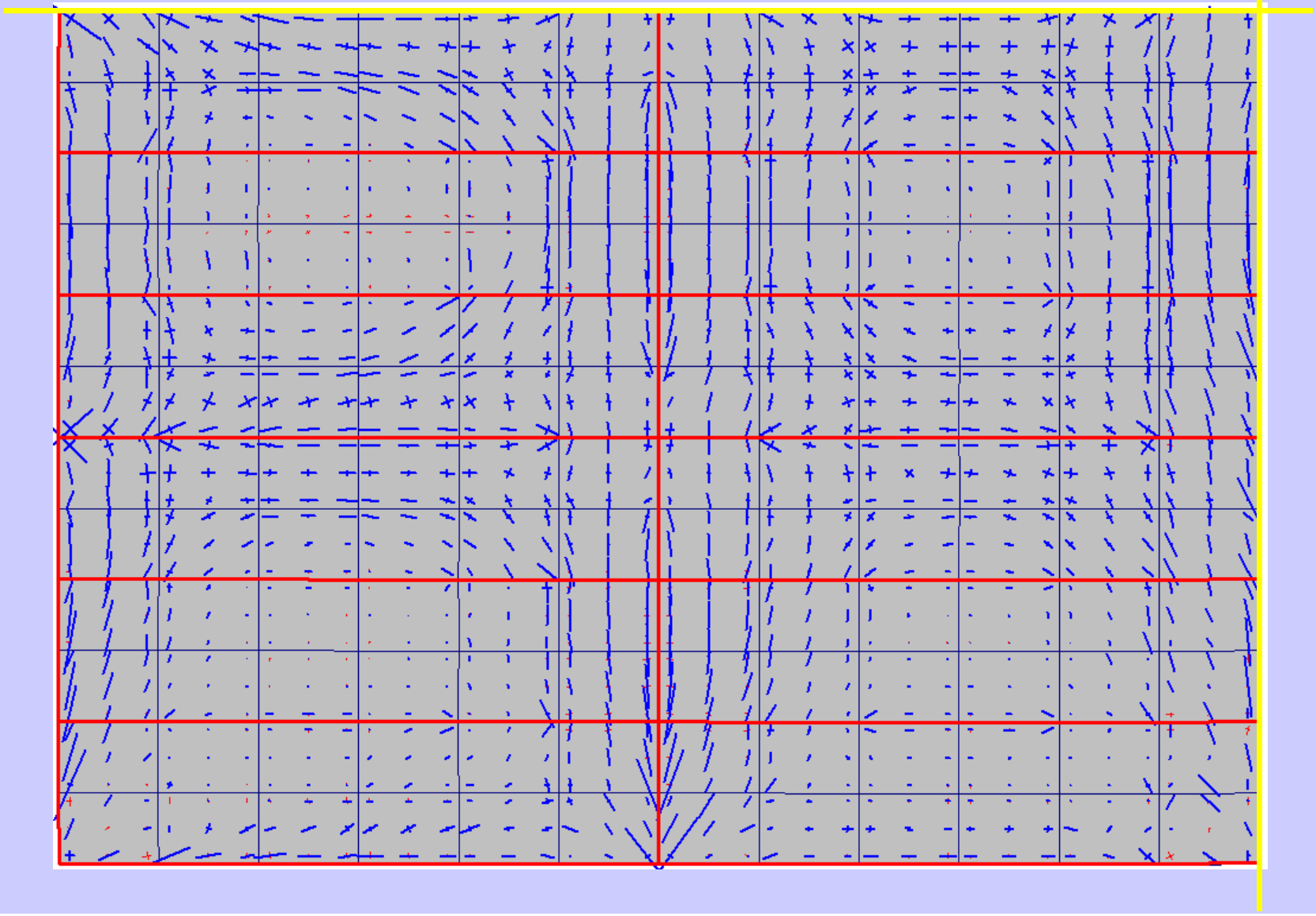
400°C

Example: Principal membrane tractions



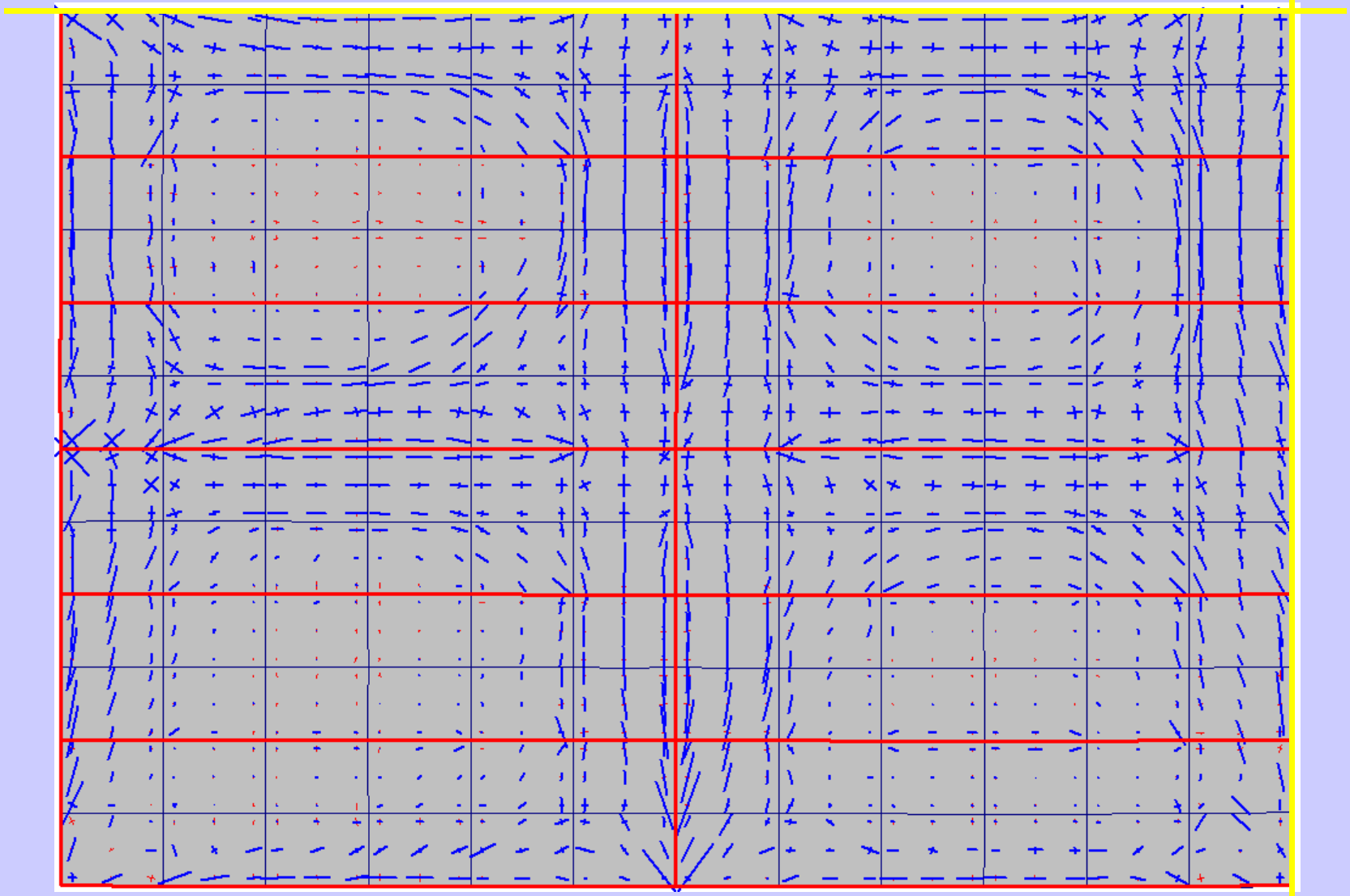
500°C

Example: Principal membrane tractions



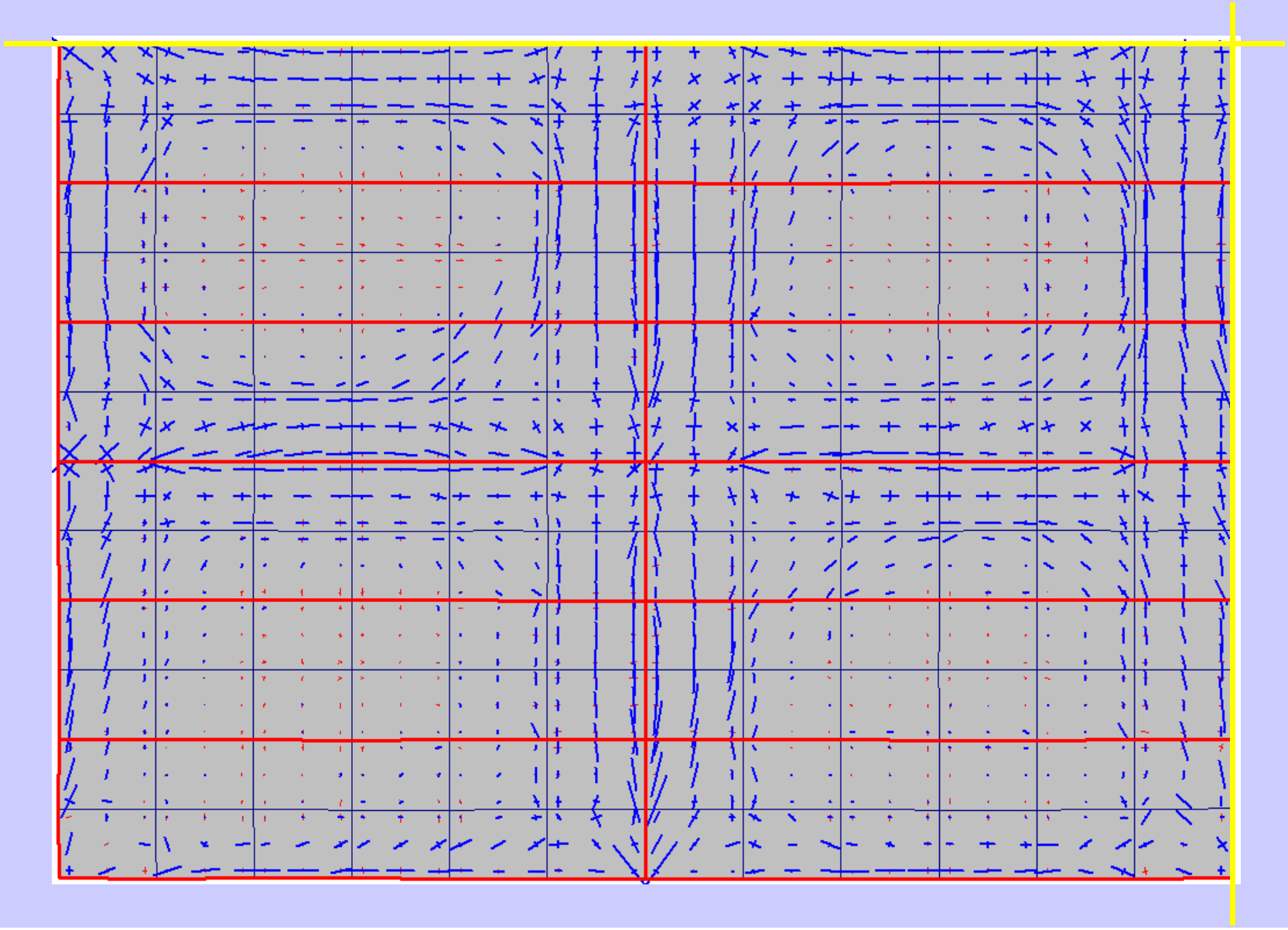
600°C

Example: Principal membrane tractions



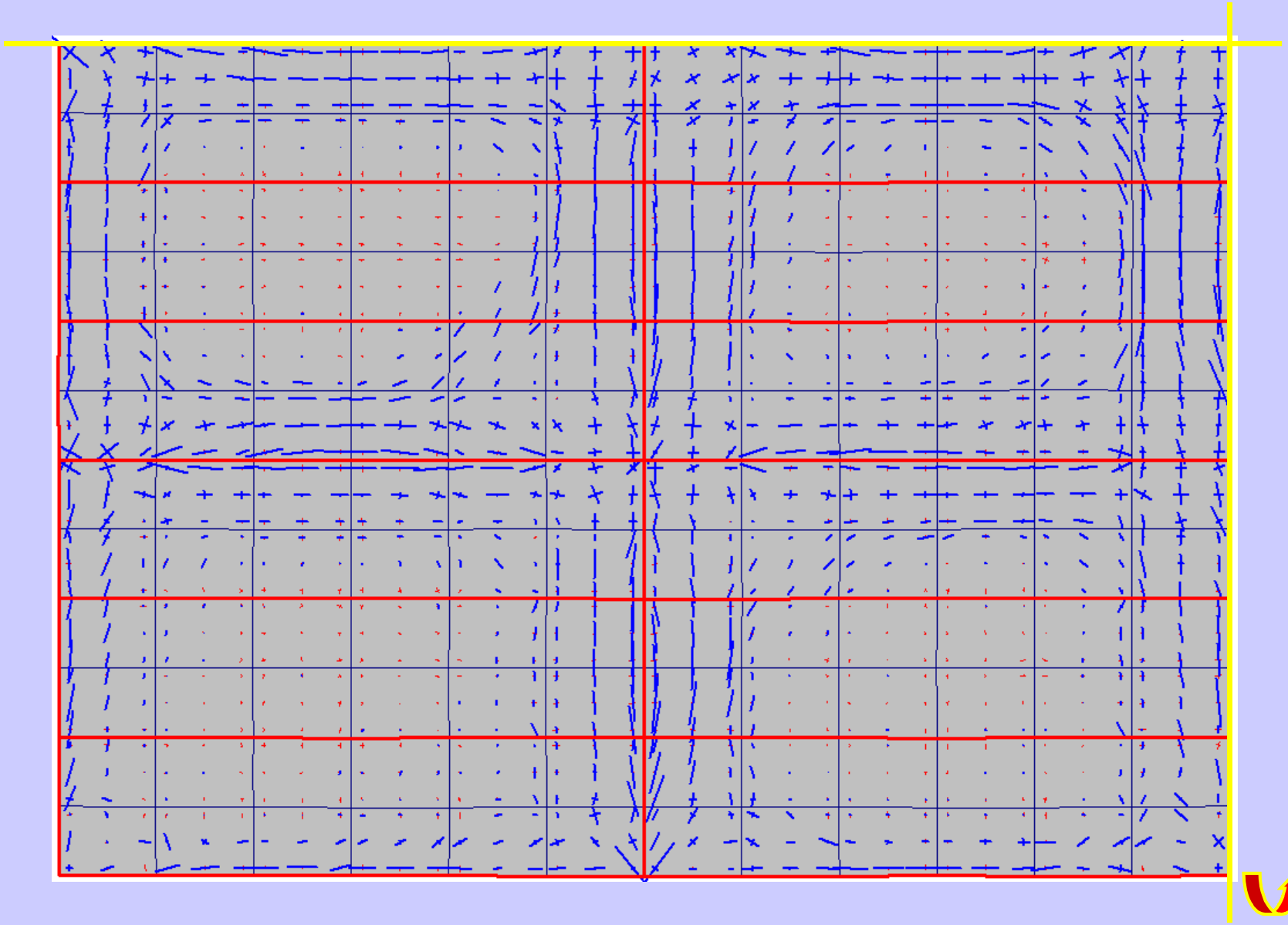
700°C

Example: Principal membrane tractions



800°C

Example: Principal membrane tractions

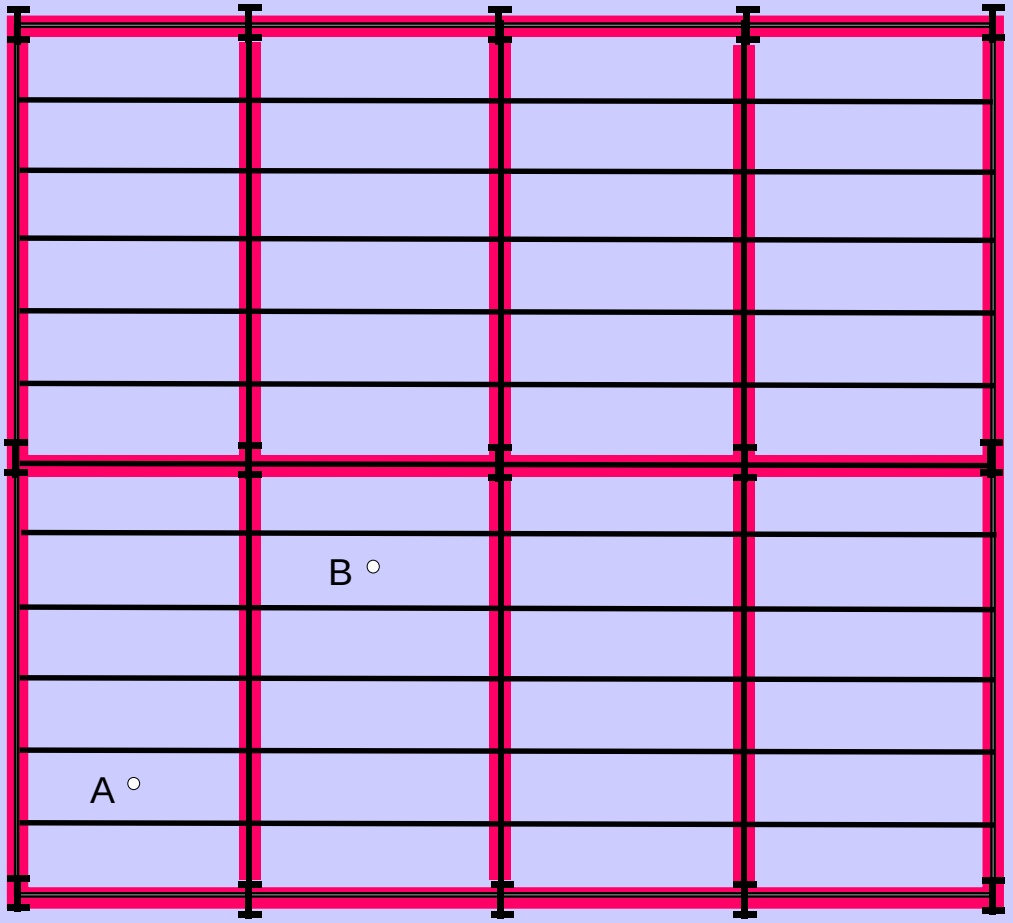


900°C

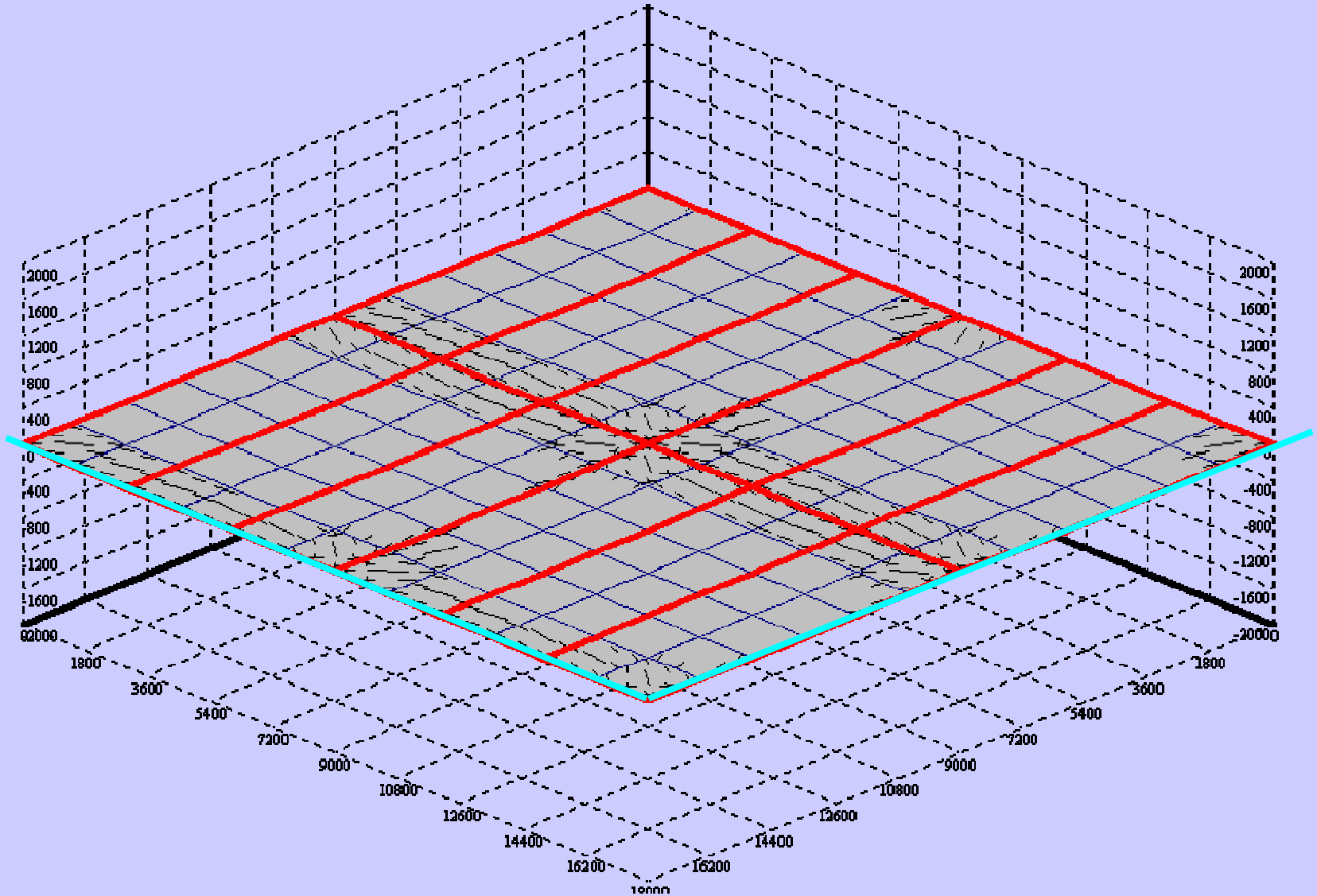
Structural fire resistance methods

Non-square structural frames:

Much lower enhancement of capacity due to tensile membrane action.

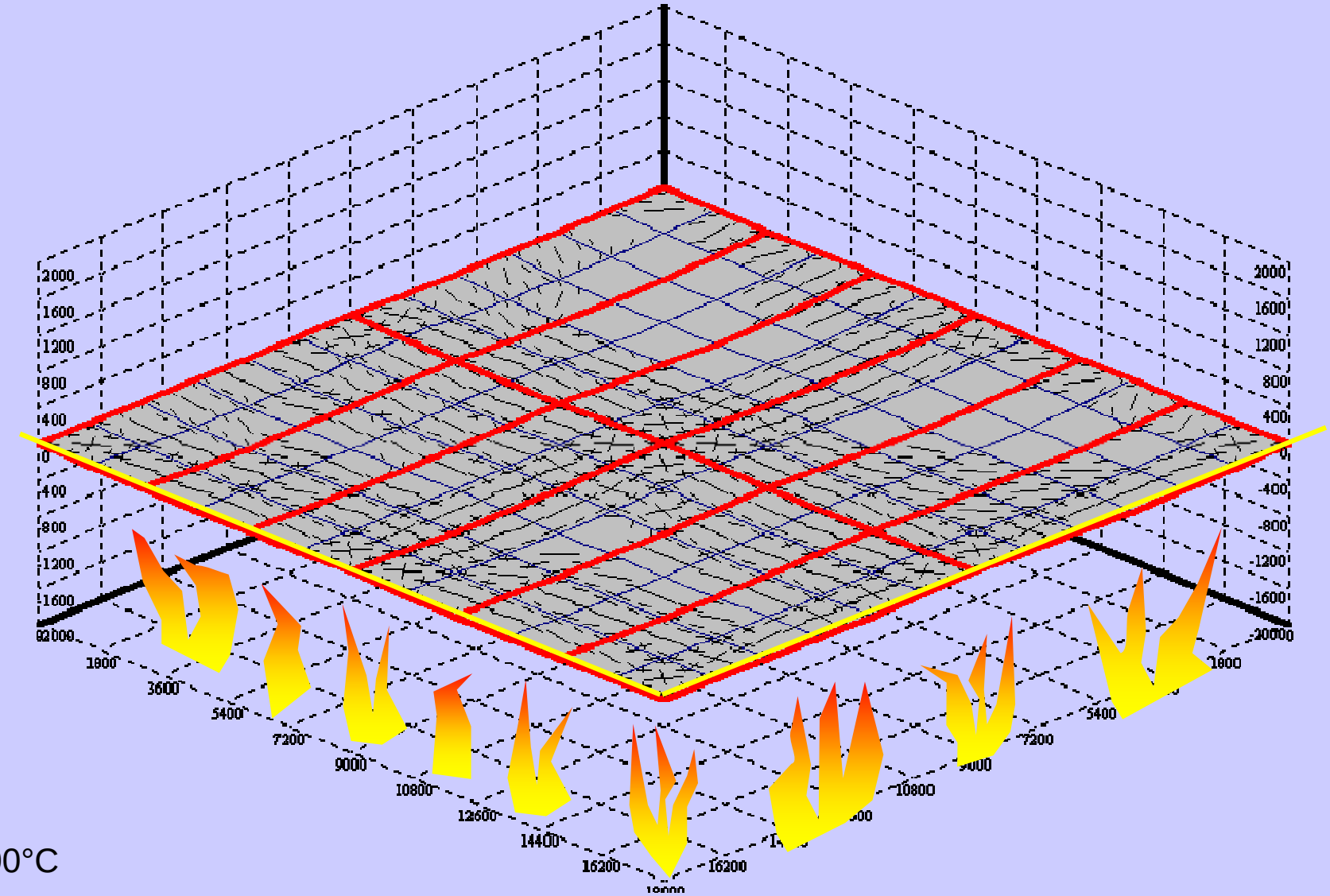


Protection Regime 2: Deflection profile



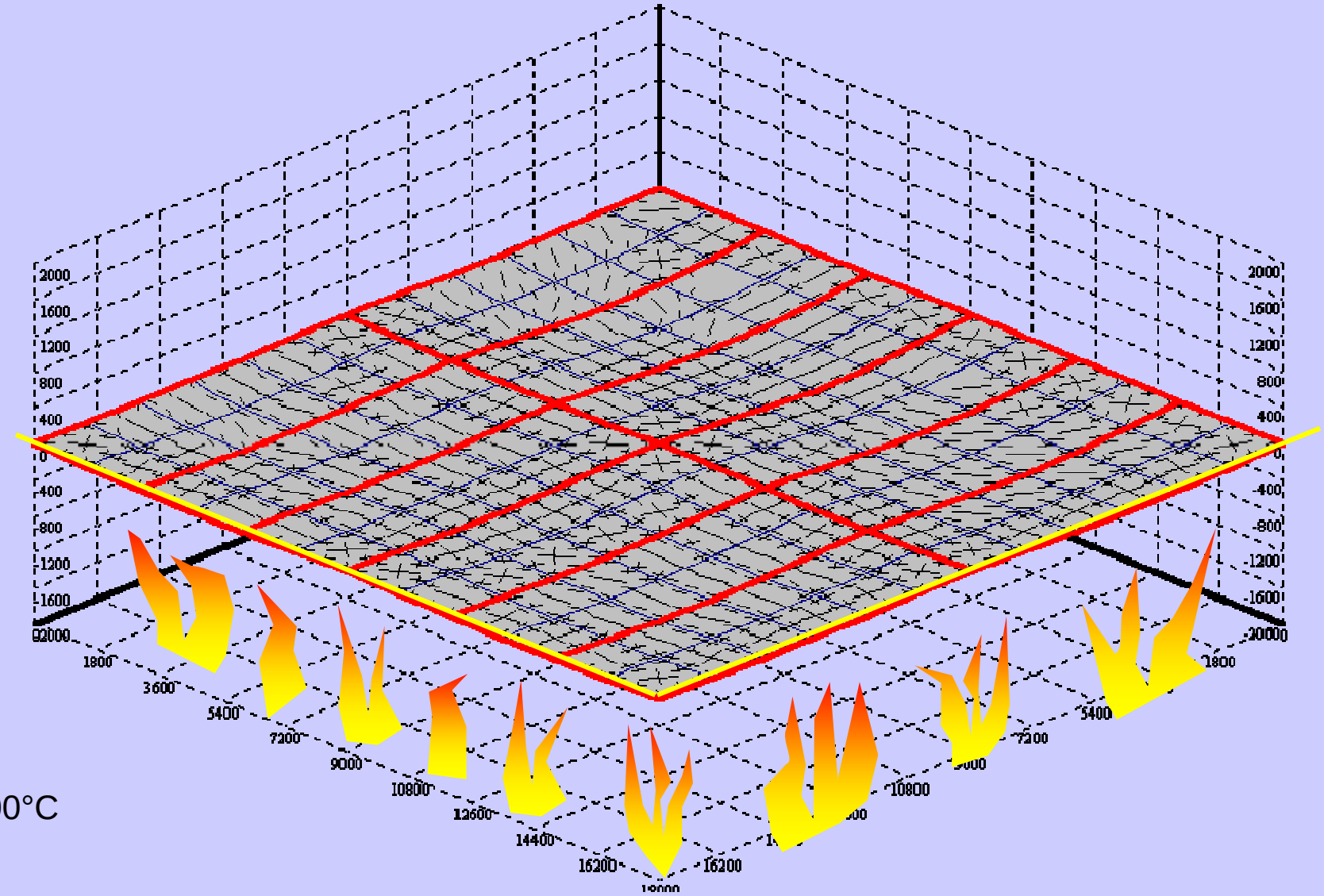
20°C

Protection Regime 2: Deflection profile

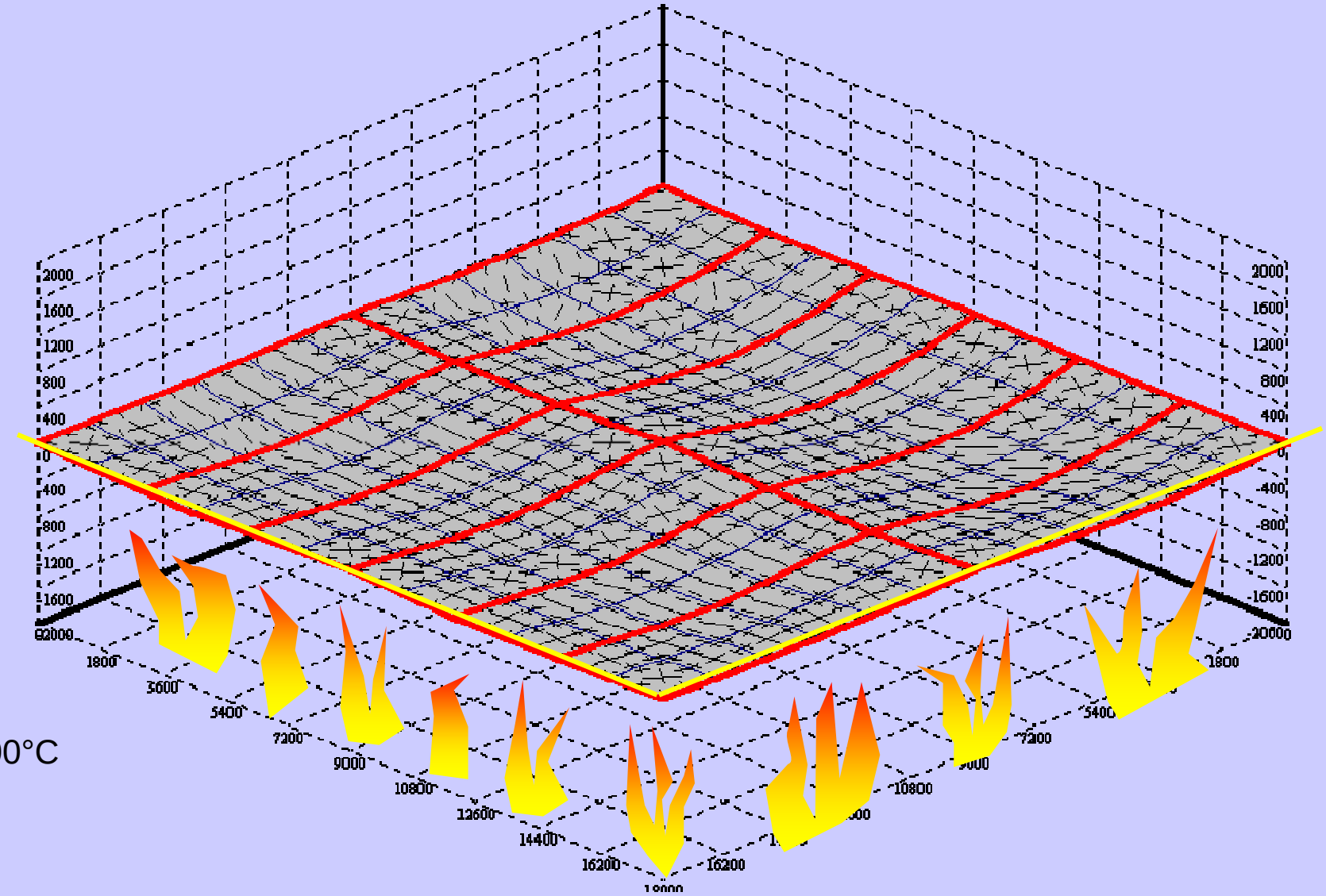


200°C

Protection Regime 2: Deflection profile



Protection Regime 2: Deflection profile



600°C

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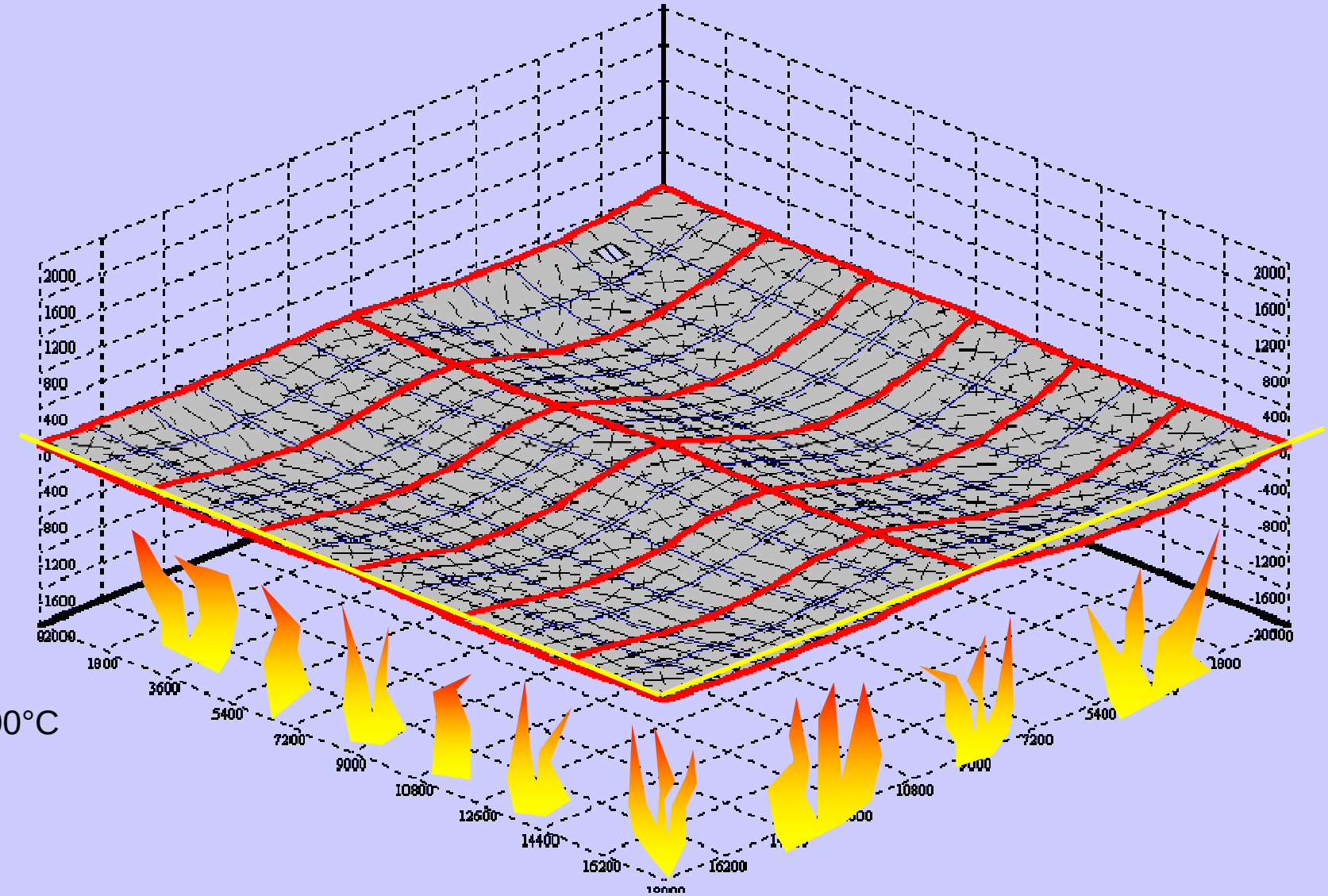
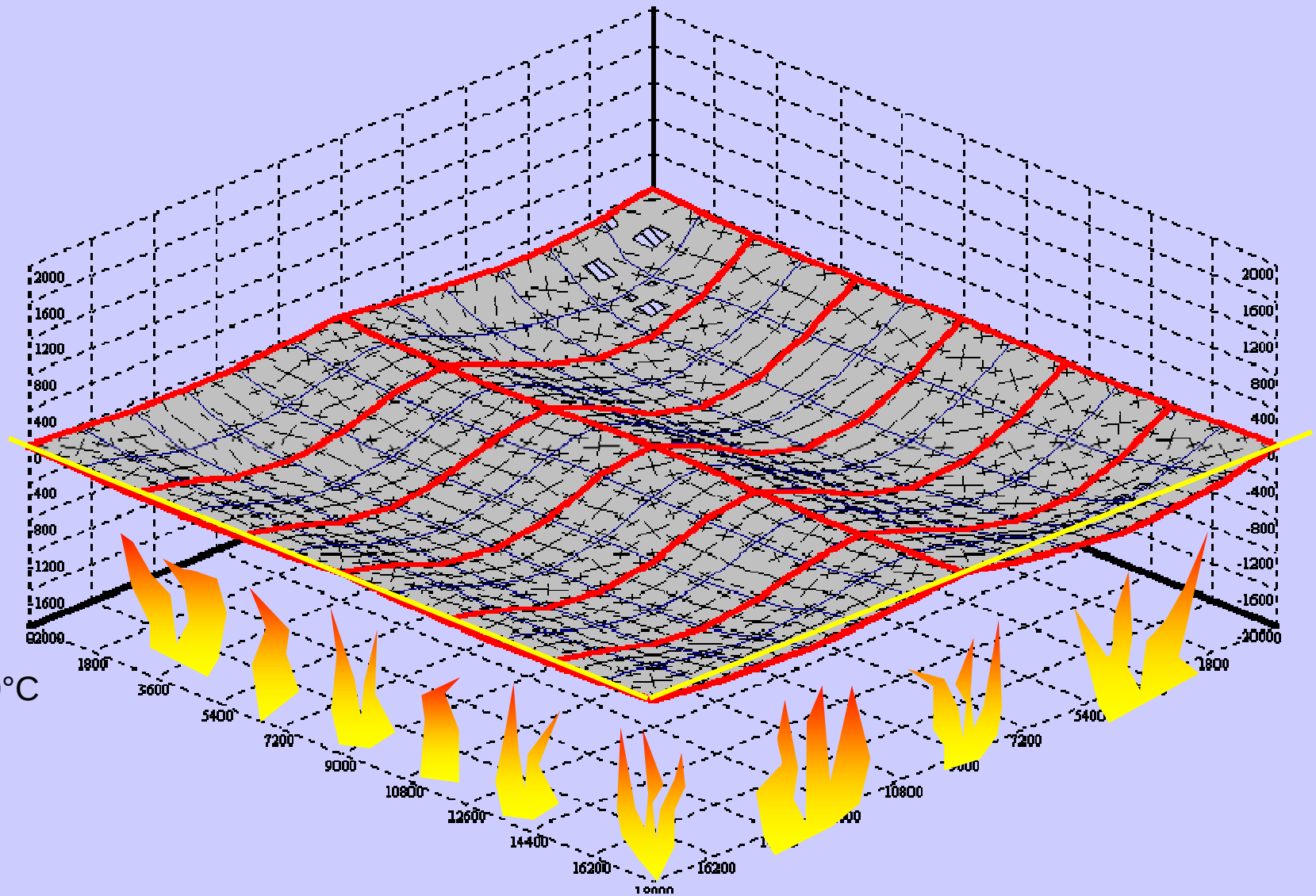


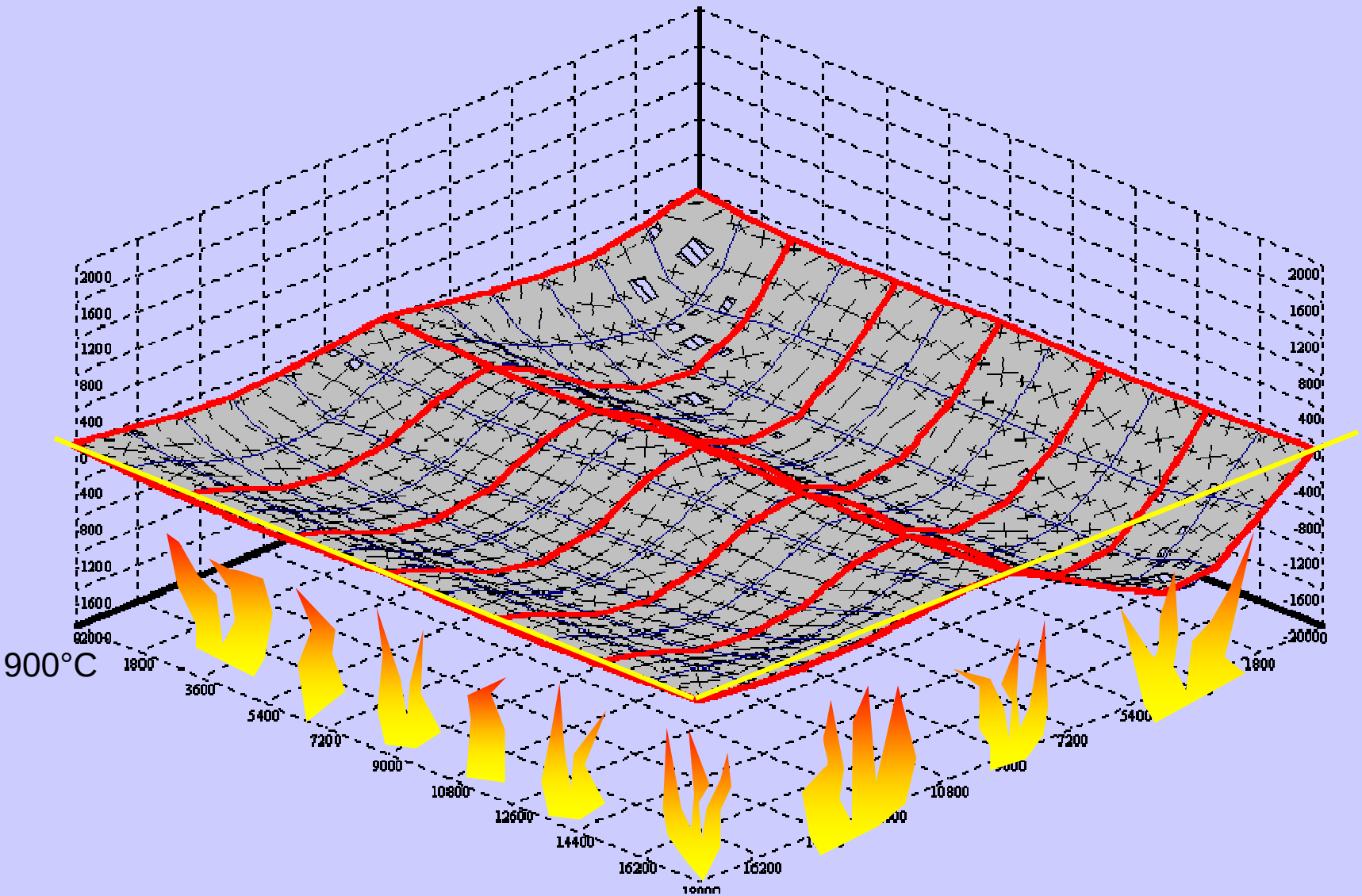
700°C

Protection Regime 2: Deflection profile

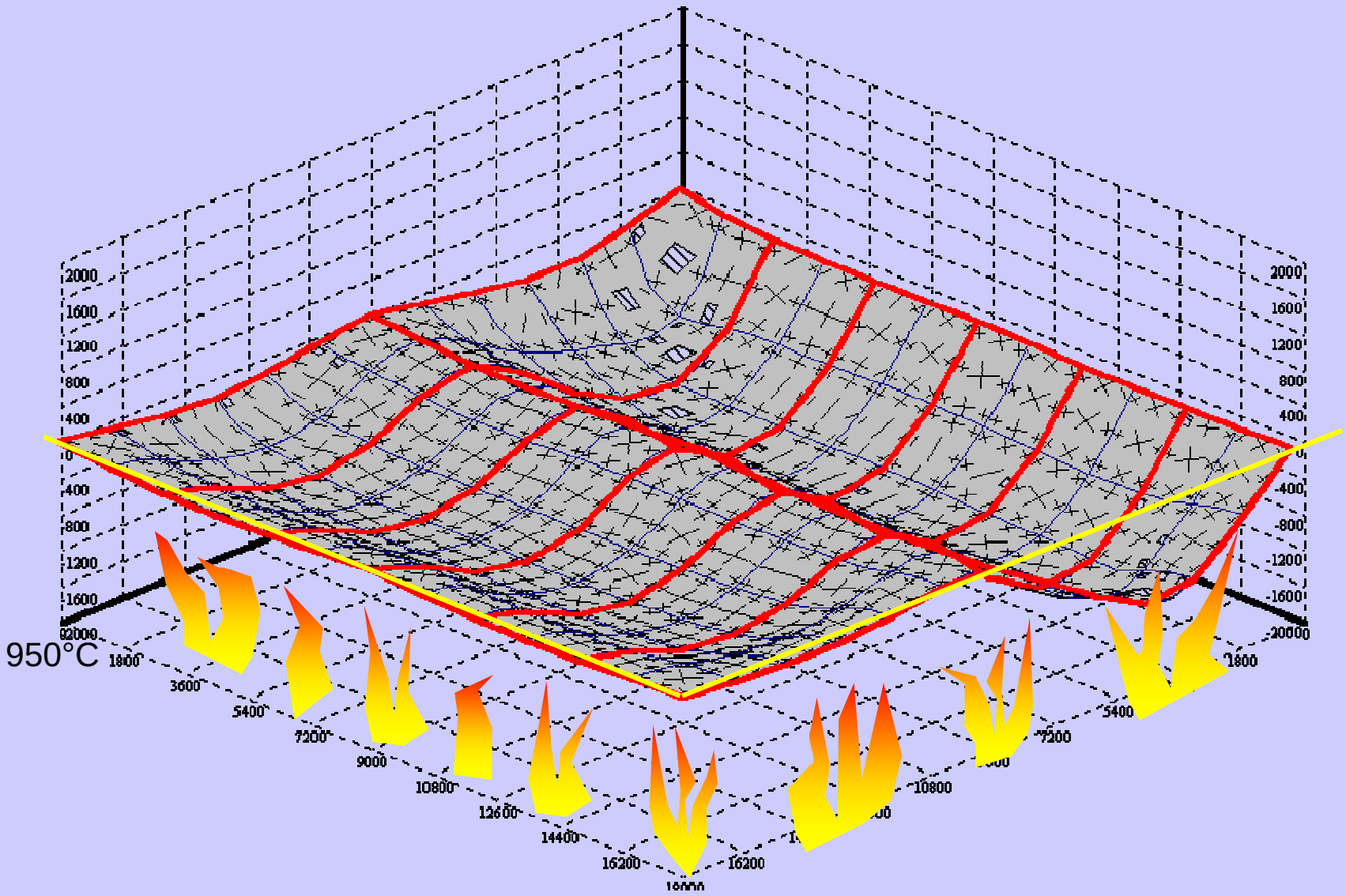


800°C

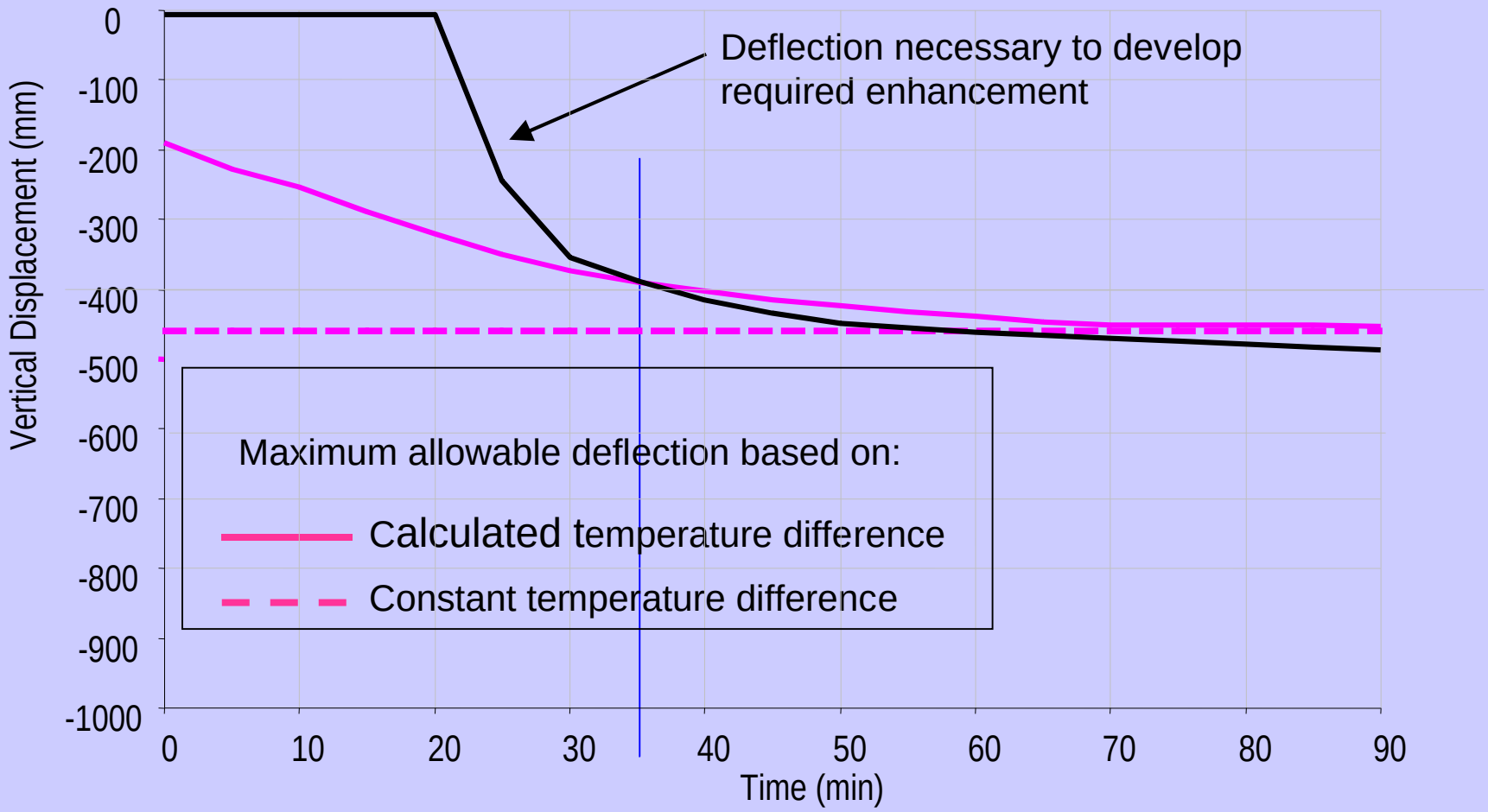
Protection Regime 2: Deflection profile



Protection Regime 2: Deflection profile

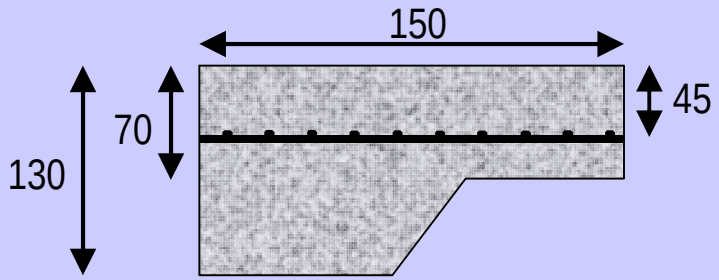


Simplified BRE Design Method

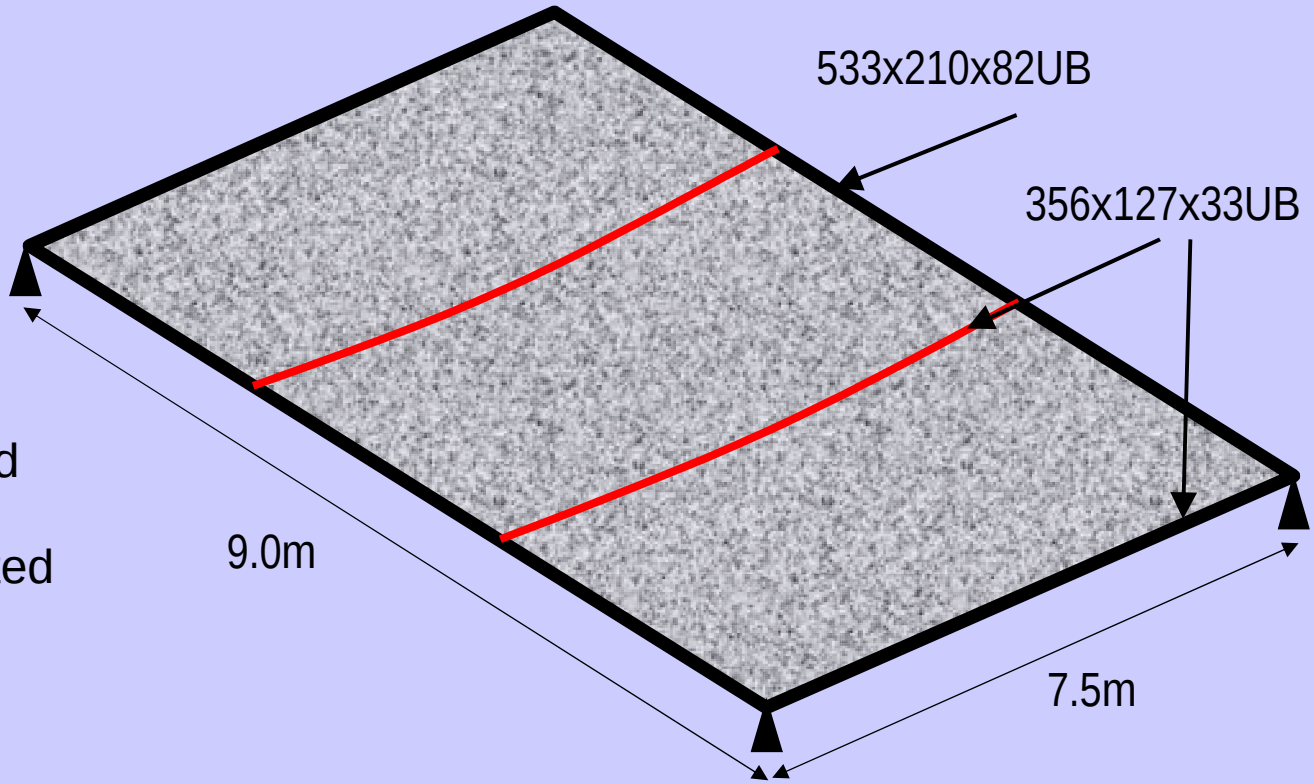


Maximum allowable deflection = $\frac{\alpha(T_2 - T_1)l^2}{19.2h} + \sqrt{\frac{0.5 f_y}{E} \times \frac{3}{8} L^2}$

Example for comparison



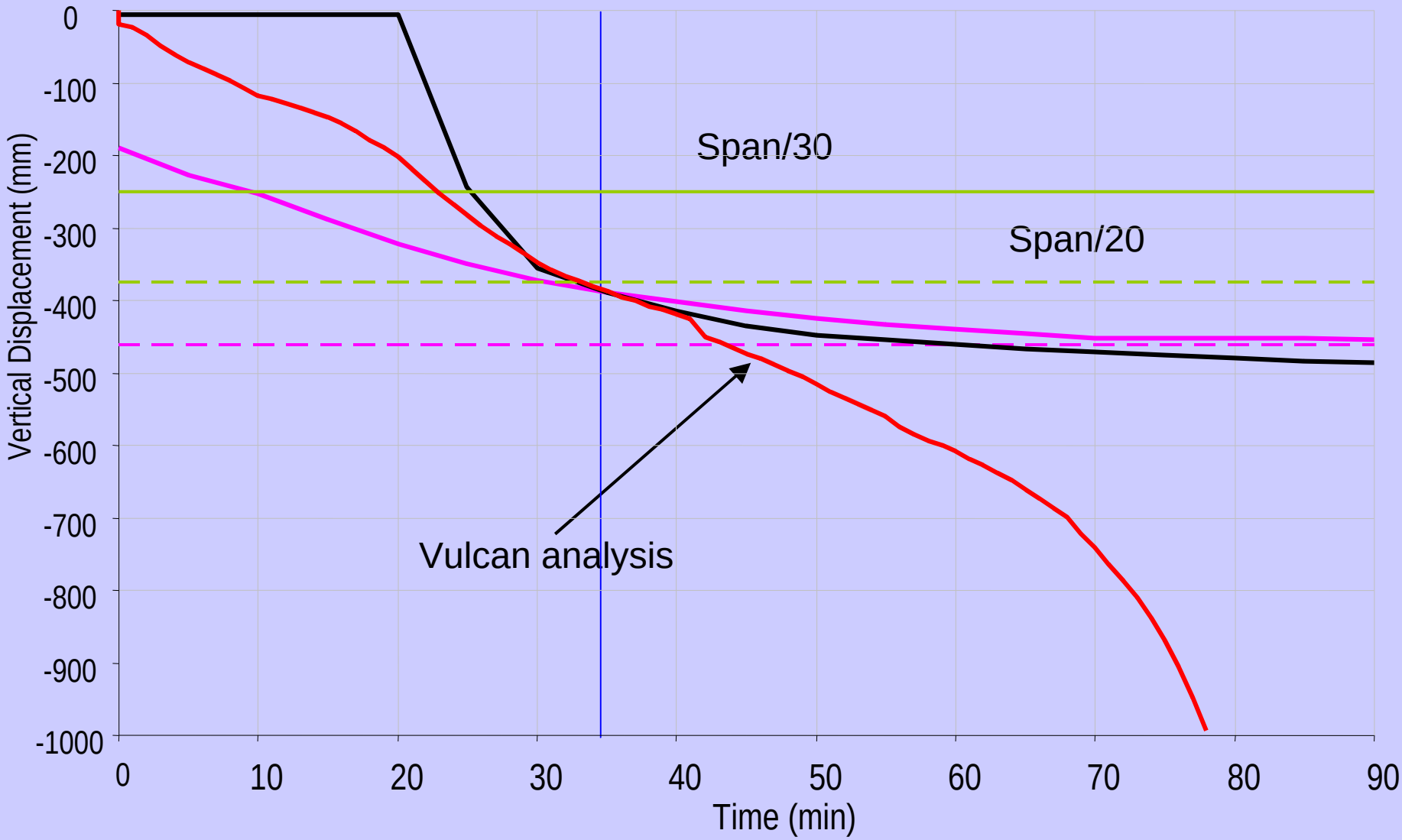
Composite slab detail



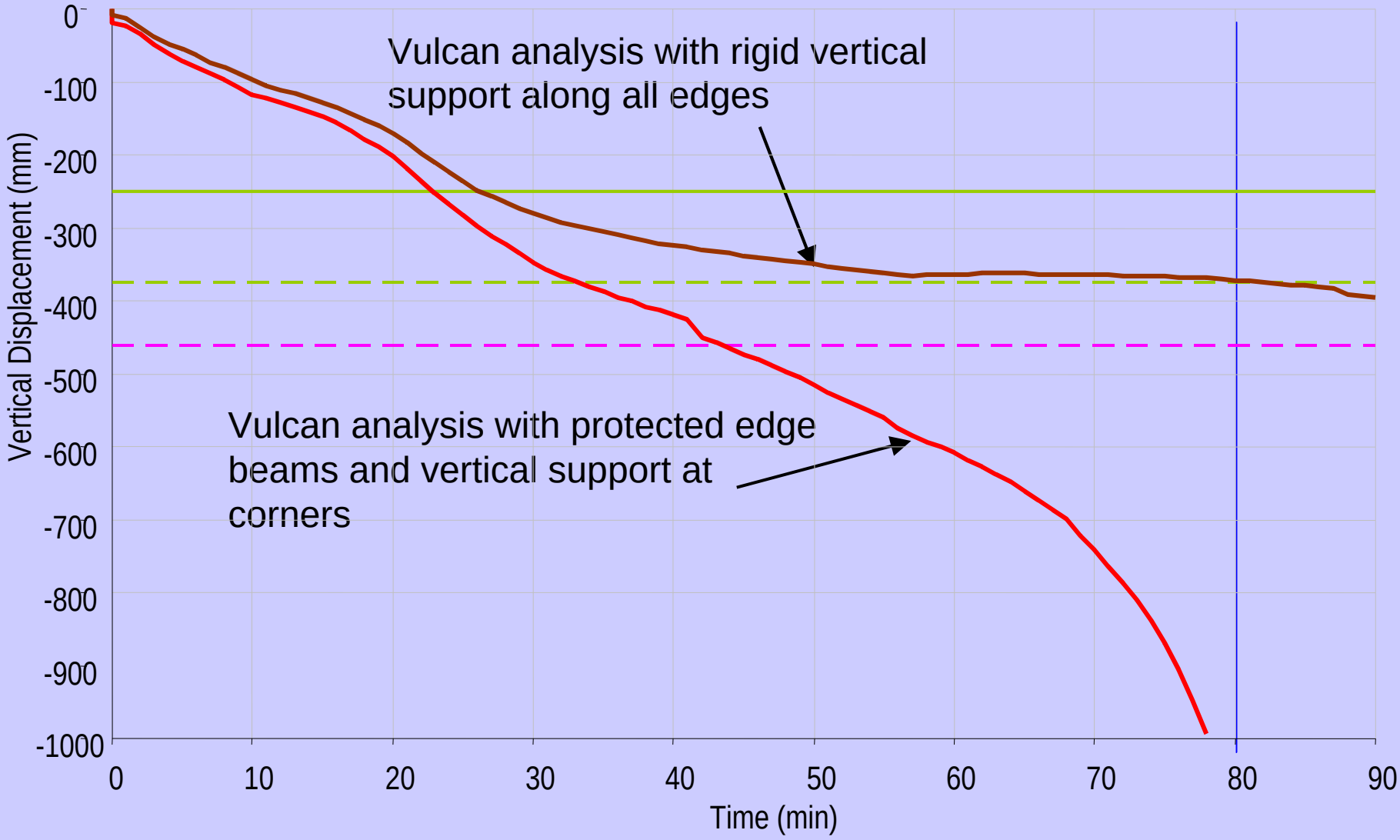
Unprotected beam

Fire protected beam

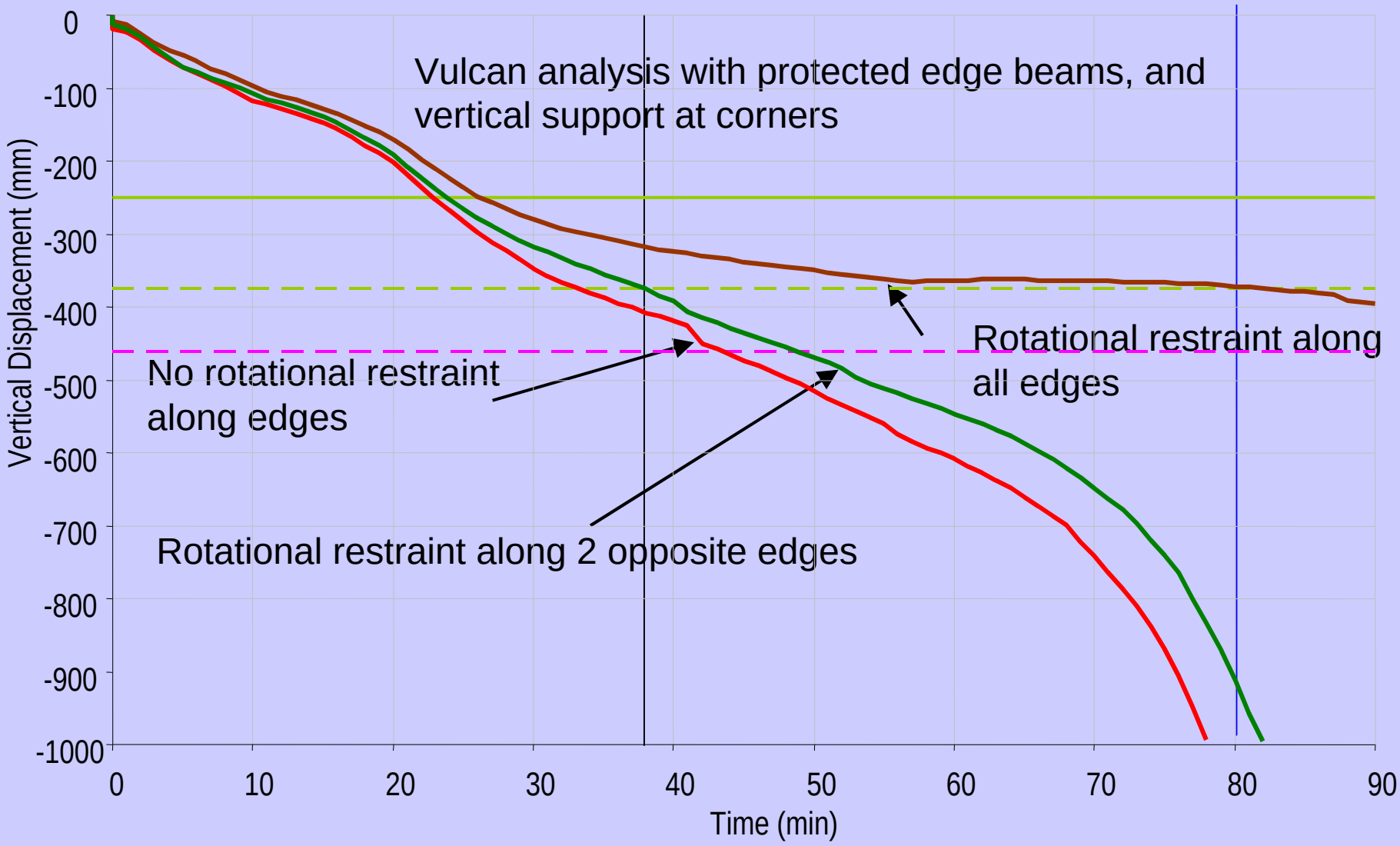
Comparisons



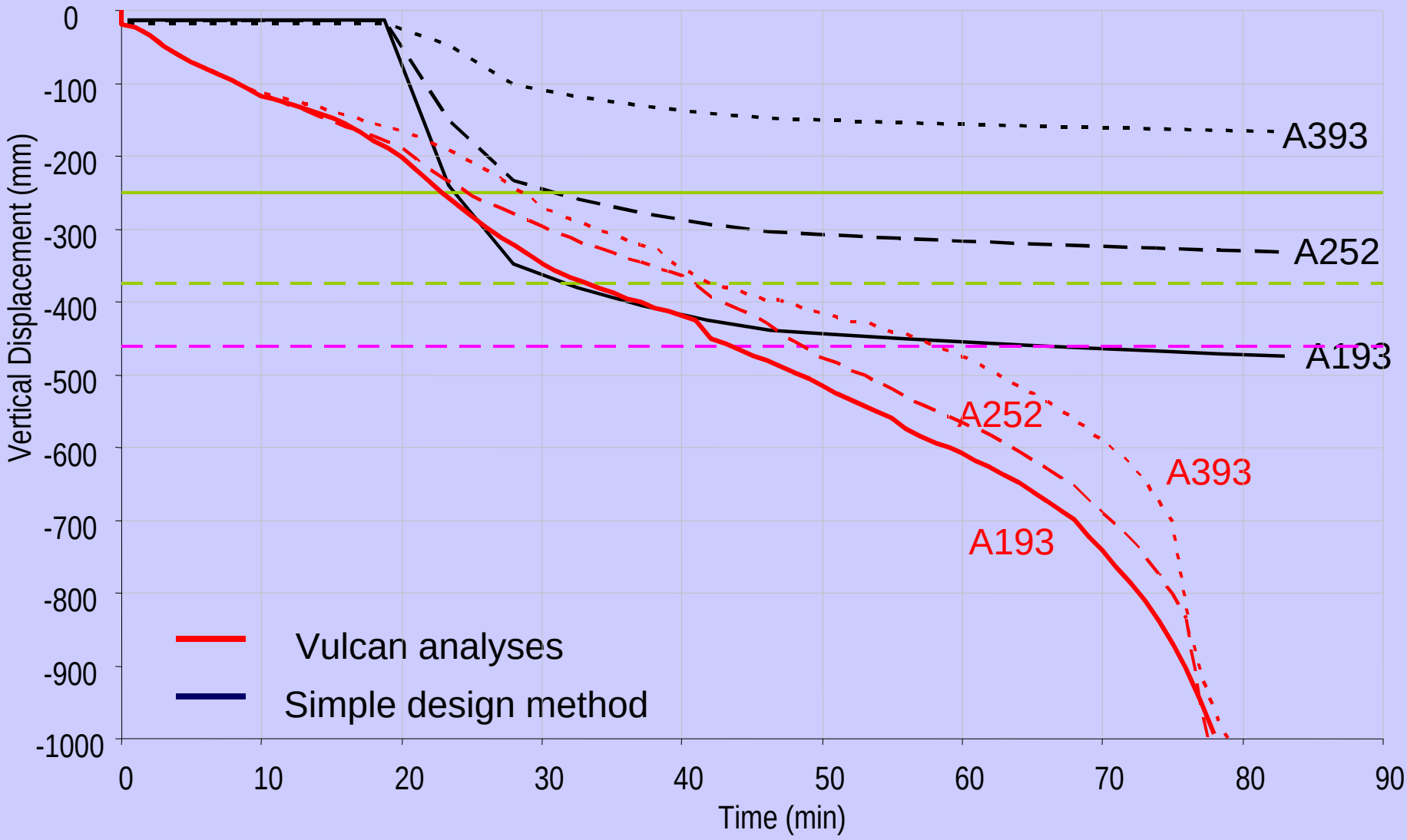
Effect of Vertical Edge Support



Effect of Rotational Edge Continuity



Effect of increasing reinforcement



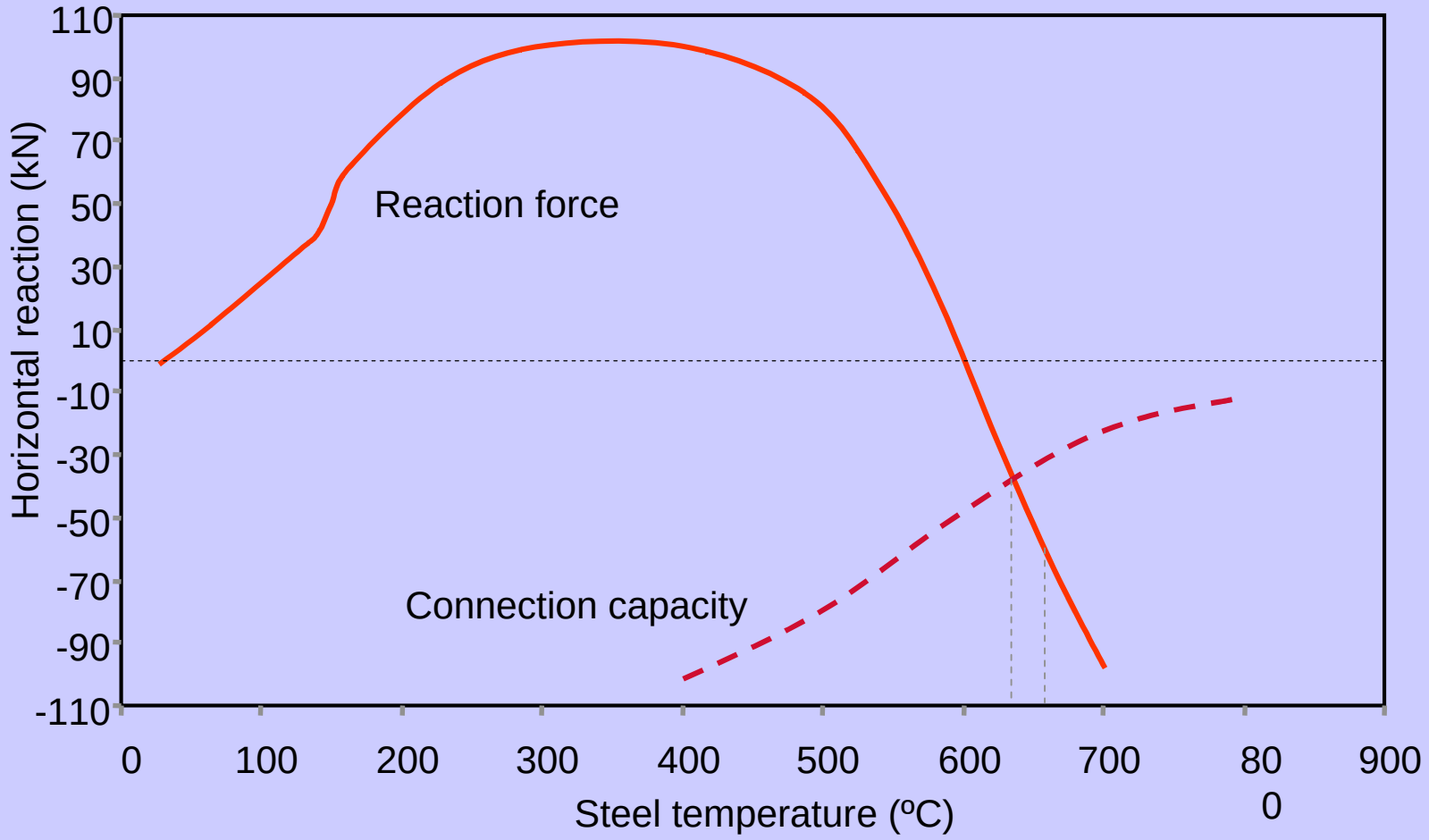
Robustness

- Connection forces can be very large
- Need to know connection robustness as well as stiffness
- Benefit of component based approach for connections

Connection behaviour in fire

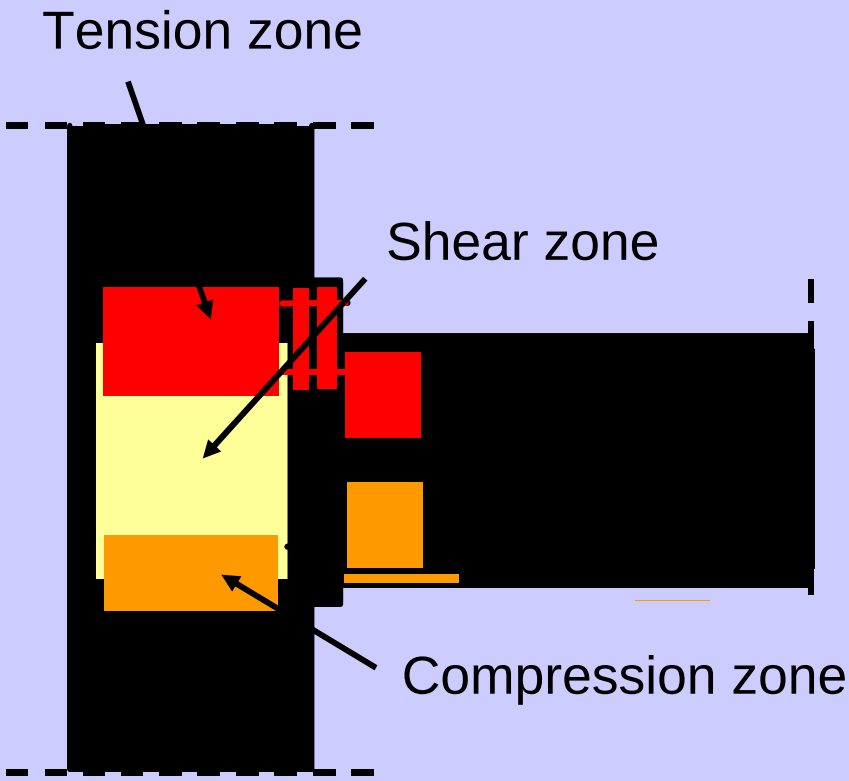
- Traditional moment-rotation characteristics inappropriate
  - Impractical
  - Axial forces important

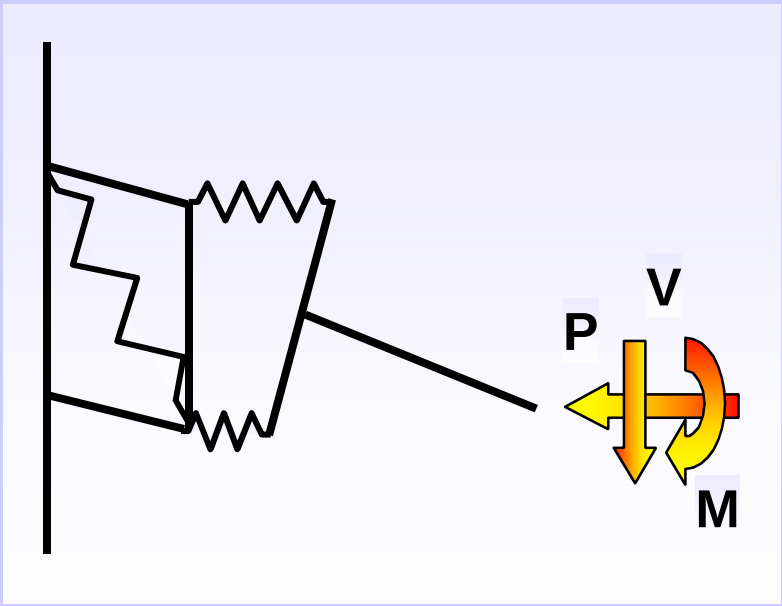
Reaction Forces at Beam Supports



The Component Method

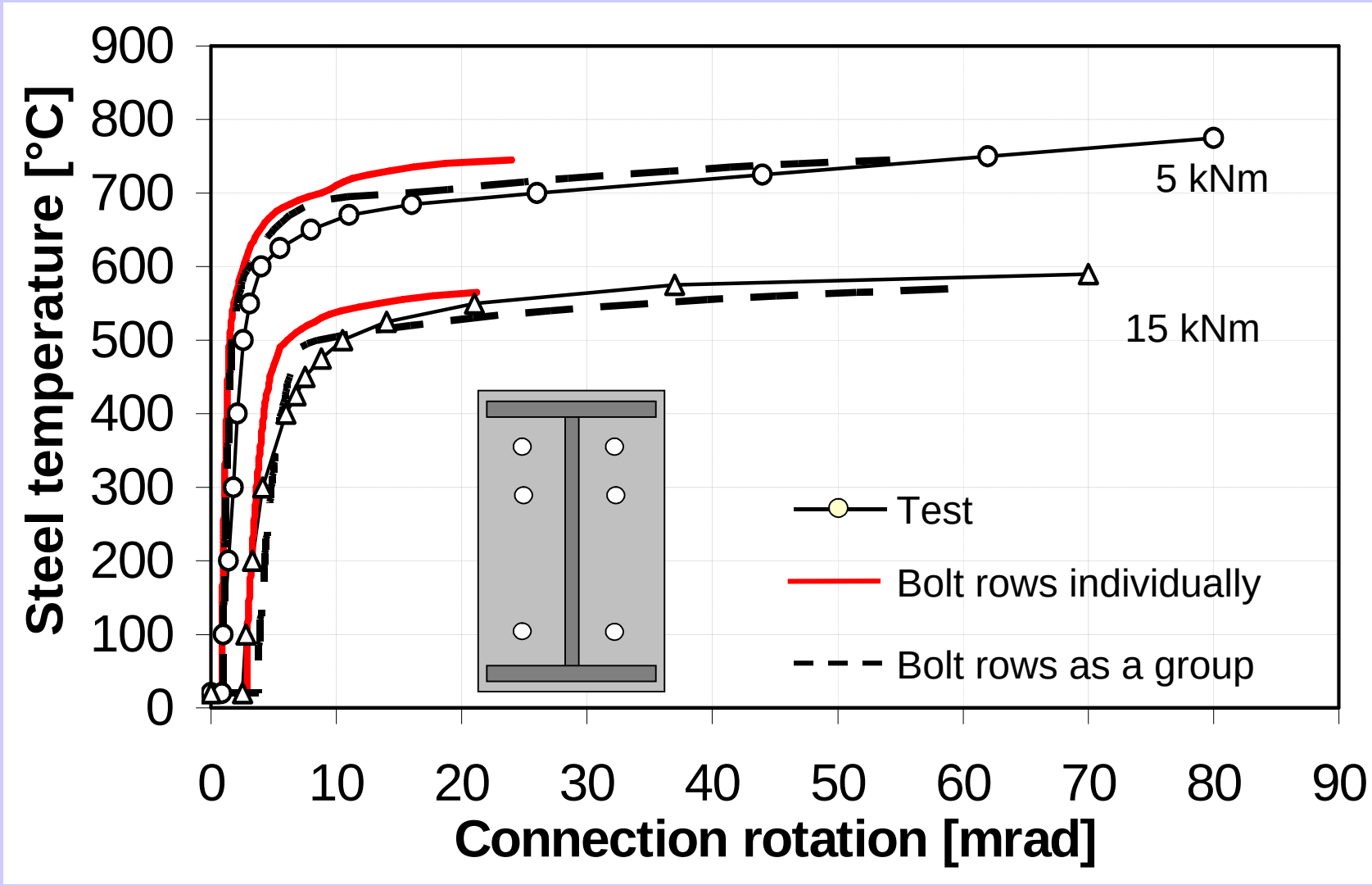
- Treats separate zones of a joint
- Behaviour of each zone represented as a spring





- Established for ambient temperature behaviour
- Currently being extended for high temperatures

Comparison with joint tests



Connection behaviour

Some failure modes

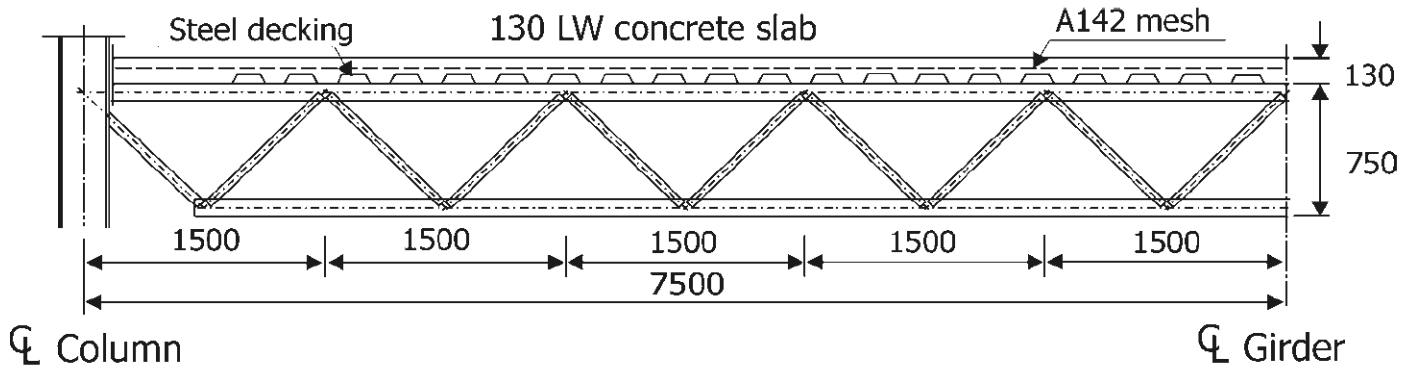
At 20°C

At 550°C

Long span systems

Standard test over 4.5m span unrepresentative

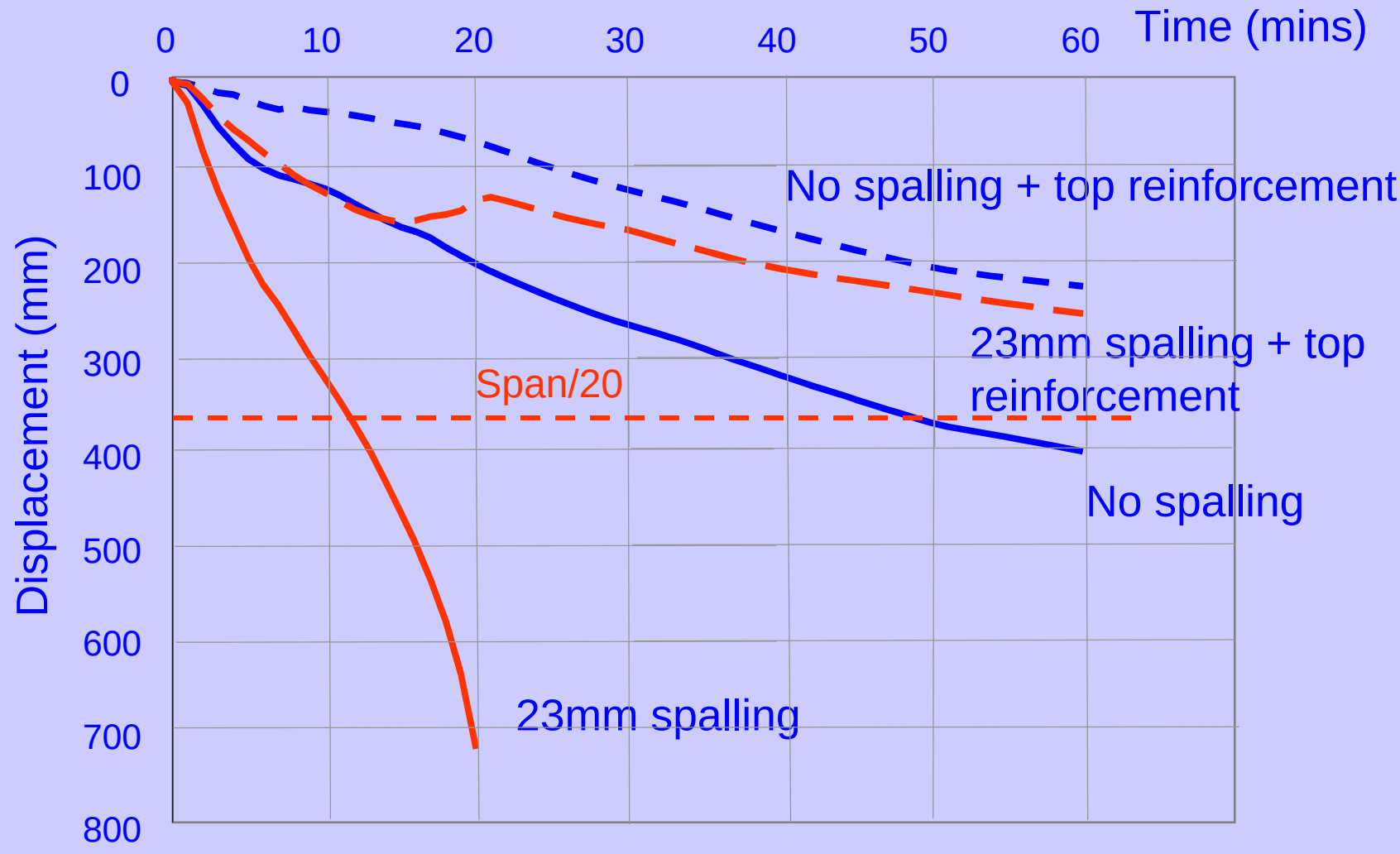
Large scale testing needed



Reinforced concrete structures

Principal concern is spalling as seen in tests and real fires

Effect of top reinforcement



Flat slab 7.5m span; 250 mm thick; 25mm cover

Conclusions

- Advanced modelling offers a performance based approach to structural fire engineering
- Potential benefits include
  - Reduced protection
  - Consistent safety
  - Improved treatment of robustness
- Some outstanding issues
  - Failure criteria
  - Connection behaviour
  - Long span systems
  - Concrete spalling

Thank you