NISTIR 6890

Fire Resistance Determination and Performance Prediction Research Needs Workshop: Proceedings

William Grosshandler
Editor

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

NISTIR 6890

Fire Resistance Determination and Performance Prediction Research Needs Workshop: Proceedings

William Grosshandler
Editor
Building and Fire Research Laboratory

September 2002

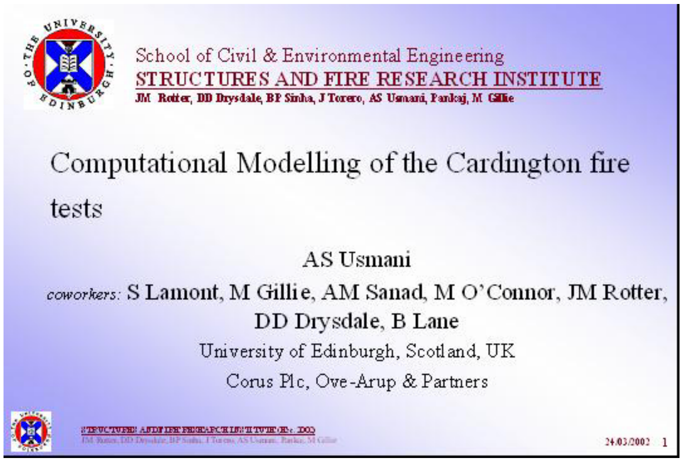
U.S. Department of Commerce
Donald L. Evans, Secretary

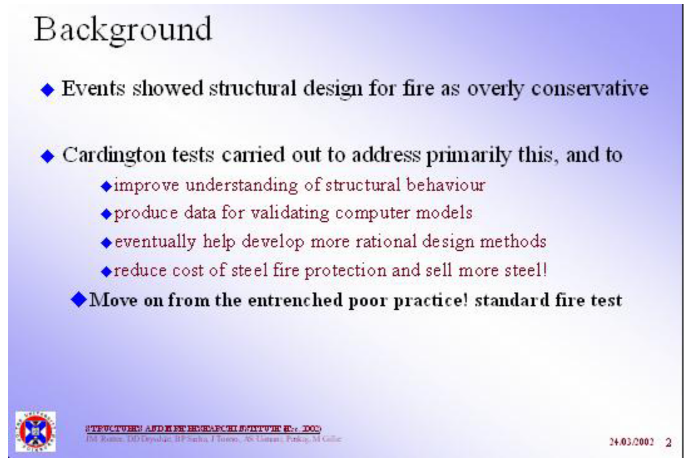
Technology Administration
Phillip J. Bond, Under Secretary of Commerce for Technology

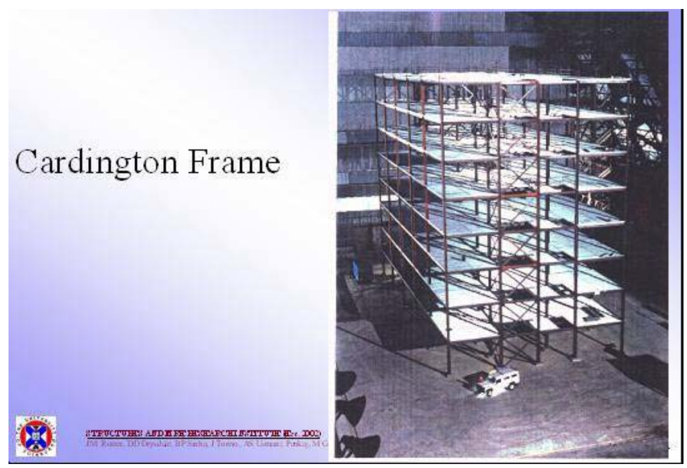
National Institute of Standards and Technology
Arden L. Bement, Jr., Director

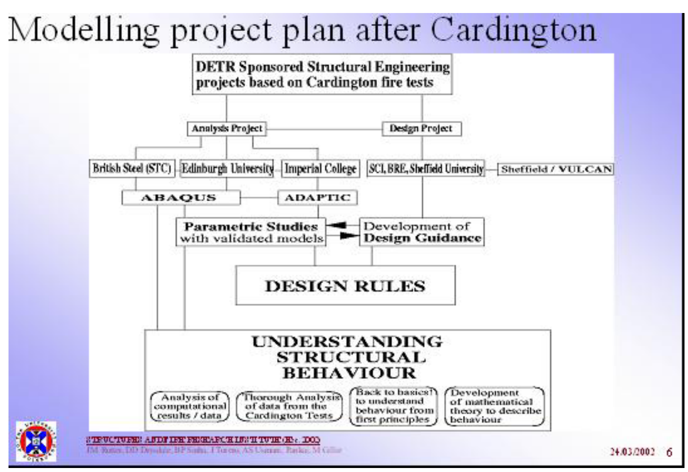
G. Simulation of Cardington Fire Tests

Asif Usmani,
University of Edinburgh, UK









Key equation

$$\varepsilon_{\text{total}} = \varepsilon_{\text{thermal}} + \varepsilon_{\text{mechanical}}$$

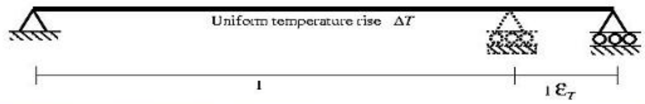
$\varepsilon_{\text{total}}$ => Displacements

$\varepsilon_{\text{mechanical}}$ => Stresses

Thermal expansion

$$\varepsilon_{\text{thermal}} \Rightarrow \boxed{\varepsilon_T = \alpha \Delta T}$$

Unrestrained thermal expansion



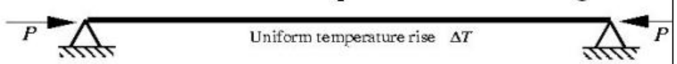
$$\varepsilon_{\text{total}} = \varepsilon_t = \varepsilon_T = \alpha \Delta T$$

$$\varepsilon_{\text{mechanical}} = \varepsilon_m = 0$$

24.03.2002 8

Thermal expansion

Restrained thermal expansion: Pre-buckling



$$\varepsilon_t = \varepsilon_T + \varepsilon_m = 0$$

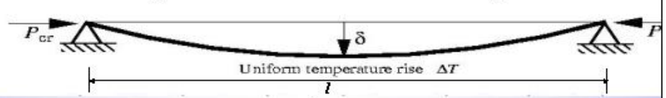
$$\varepsilon_m = -\varepsilon_T$$

$$P = EA\,\varepsilon_m = -EA\,\varepsilon_T = -EA\,\alpha \Delta T$$

24.03.2002 9

Thermal expansion

Buckling due to restrained thermal expansion



$$P_{cr} = \frac{\pi^2 EI}{l^2}$$

$$EA\alpha\Delta T = \frac{\pi^2 EI}{l^2}$$

$$\Delta T_{cr} = \frac{\pi^2}{\alpha \lambda^2}$$

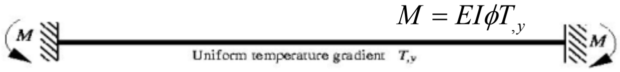
24.03.2002 10

Thermal bowing

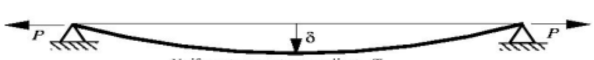
Curvature => $\phi = \alpha T_{,y}$

Thermal Bowing with ends restrained against rotation

$$M = EI\phi T_{,y}$$



Thermal Bowing with ends restrained against translation

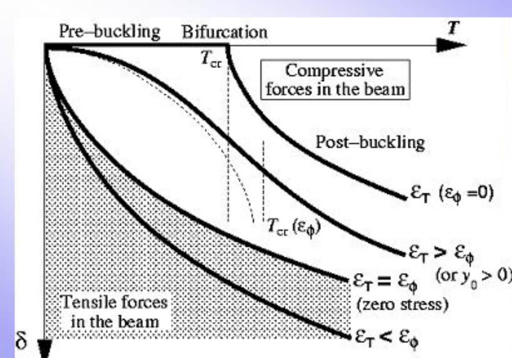


$$\boxed{\varepsilon_\phi = 1 - \frac{\sin \frac{l\phi}{2}}{\frac{l\phi}{2}}}$$

STRUCTURES AND FIRE RESEARCH INSTITUTE (Est. 2002)
JM Rotter, DD Drysdale, BP Sinha, J Torero, AS Usmani, Pankaj, M Gillie

24/03/2002 11

Various temperature-deflection responses

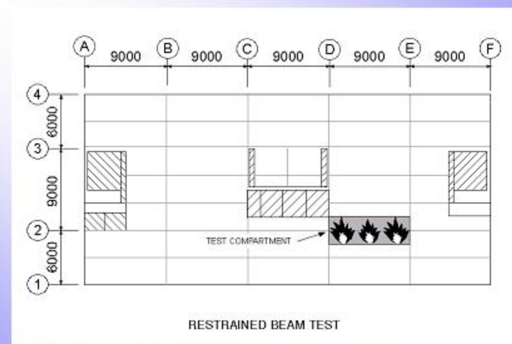


24.03.2002 12

Main principles to interpret model output

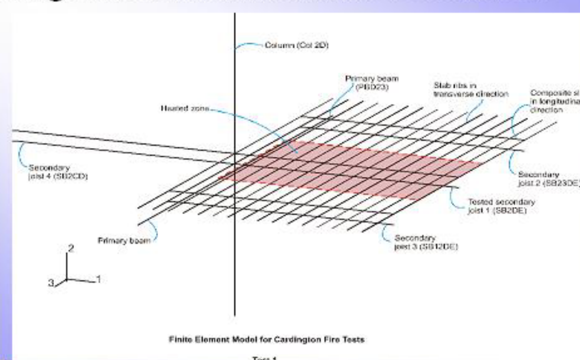
- **Fire effect on beams and slabs can adequately be described in terms of mean temperature increment ΔT & through depth thermal gradient $T_{,z}$**
- Restraint to lateral translation produces compression (small restraint enough)
- Thermal gradients impose curvature in unrestrained pin ended members
- Gradients induce moment in members with rotationally restrained ends
- Gradients induce tension in pin-ended translationally restrained members
- Combinations of thermal expansion and bowing with various restraint conditions produce a large range of deflection and internal force patterns
- **In slabs and other 2D members compatibility of displacements in the two directions may govern internal forces and displacements**

British Steel Test 1 (Restrained beam test)

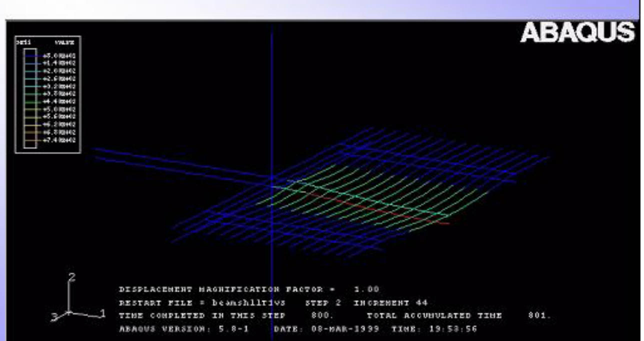


British Steel Test 1 (Restrained beam test)

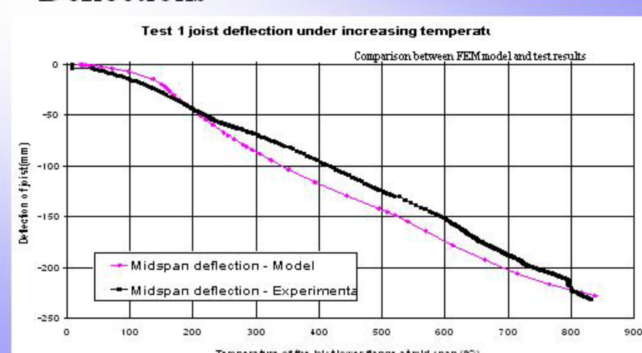
Grillage model for Restrained beam test

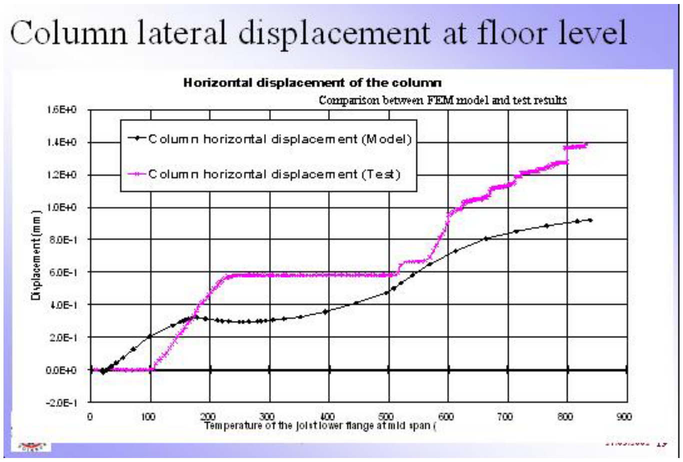


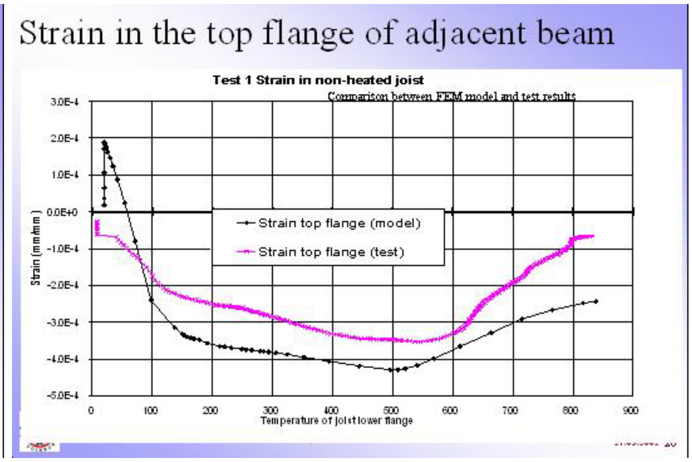
Deflected model

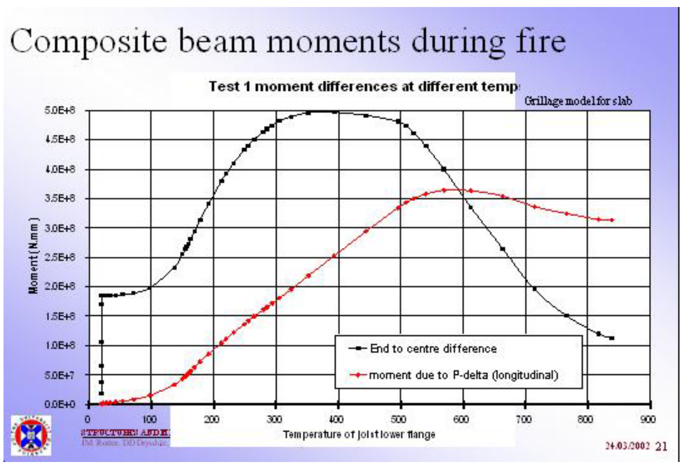


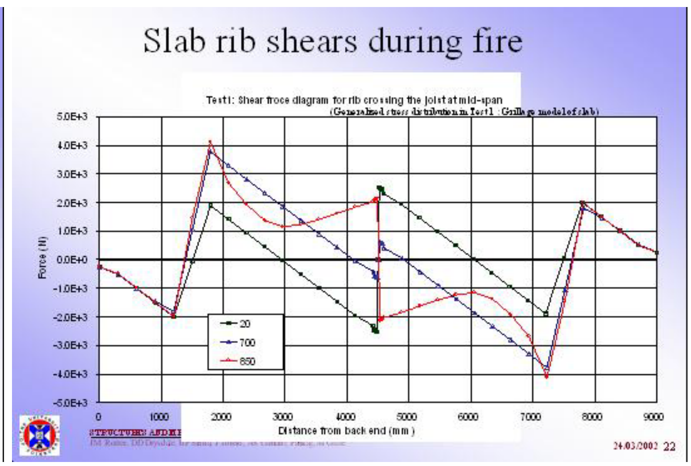
Deflections

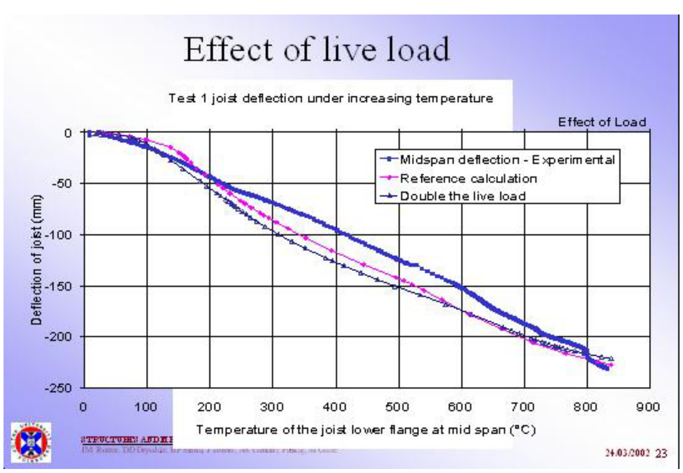


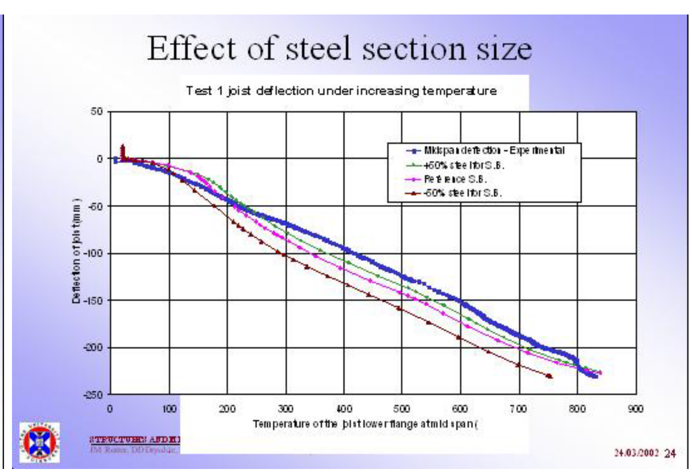

Column lateral displacement at floor level
Horizontal displacement of the column
Comparison between FEM model and test results
Column horizontal displacement (Model)
Column horizontal displacement (Test)
Displacement (mm)
Temperature of the joist lower flange at mid span (

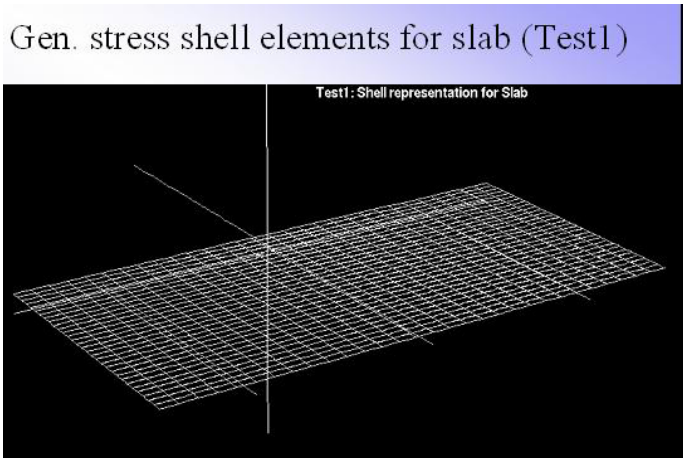

Strain in the top flange of adjacent beam
Test 1 Strain in non-heated joist
Comparison between FEM model and test results
Strain top flange (model)
Strain top flange (test)
Strain (mm/mm)
Temperature of joist lower flange

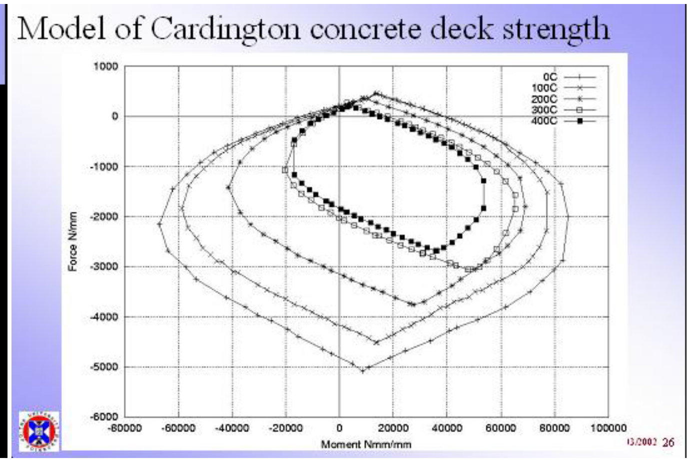

Composite beam moments during fire
Test 1 moment differences at different temp
Grillage model for slab
End to centre difference
moment due to P-delta (longitudinal)
Moment (N.mm)
Temperature of joist lower flange
24.03.2002 21

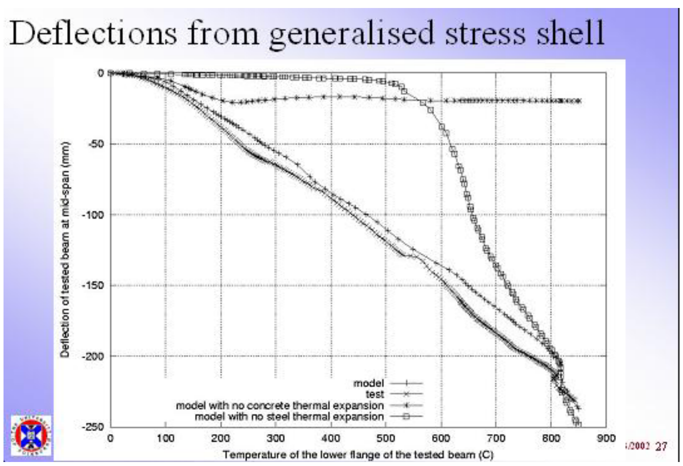

Slab rib shears during fire
Test1: Shear force diagram for rib crossing the joist at mid-span
Force (N)
Distance from back end (mm)
24.03.2002 22

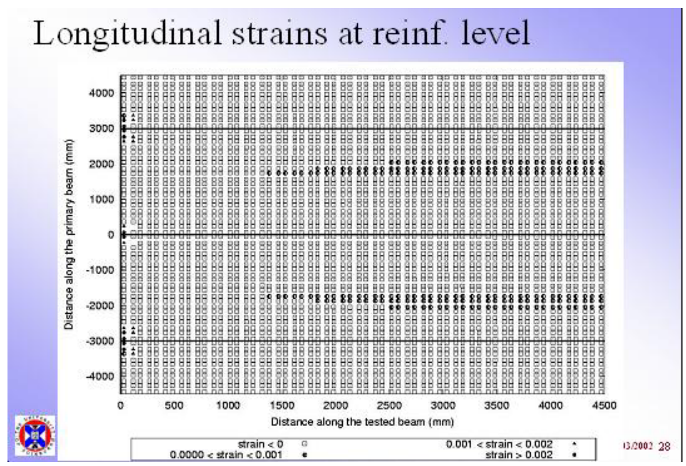

Effect of live load
Test 1 joist deflection under increasing temperature
Effect of Load
Midspan deflection - Experimental
Reference calculation
Double the live load
Deflection of joist (mm)
Temperature of the joist lower flange at mid span (°C)
24.03.2002 23

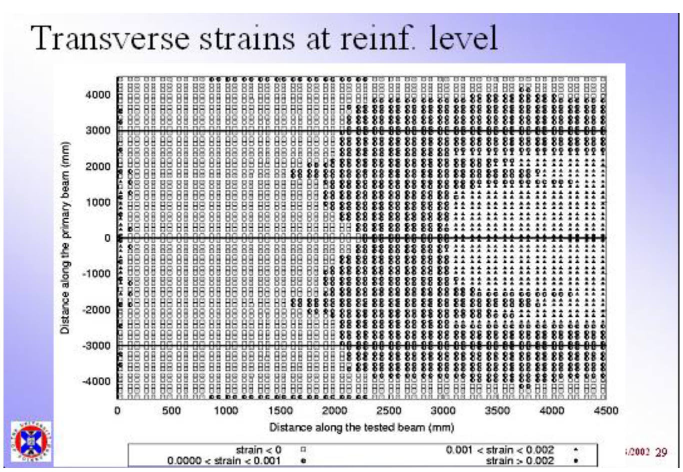

Effect of steel section size
Test 1 joist deflection under increasing temperature
Deflection of joist (mm)
Temperature of the joist lower flange at mid span (
24.03.2002 24

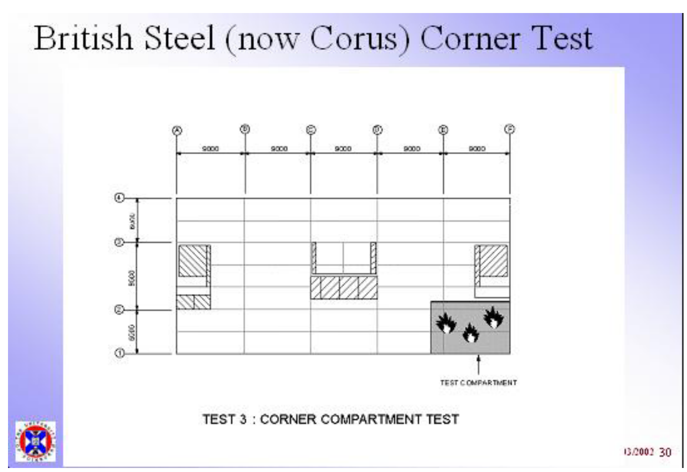

Gen. stress shell elements for slab (Test1)
Test1: Shell representation for Slab

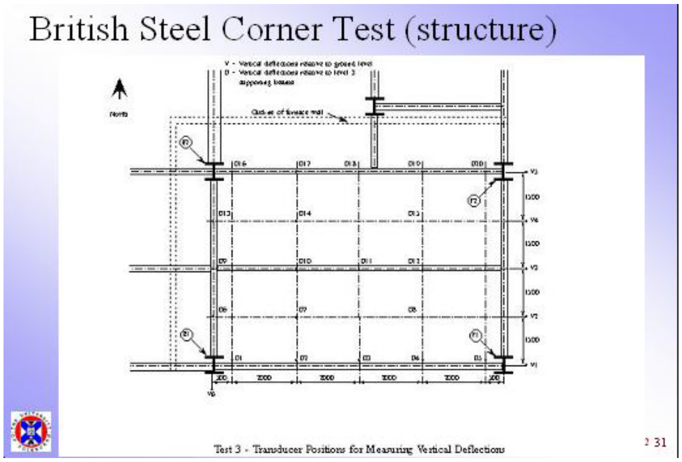

Model of Cardington concrete deck strength
0C
100C
200C
300C
400C
Force N/mm
Moment Nmm/mm
26

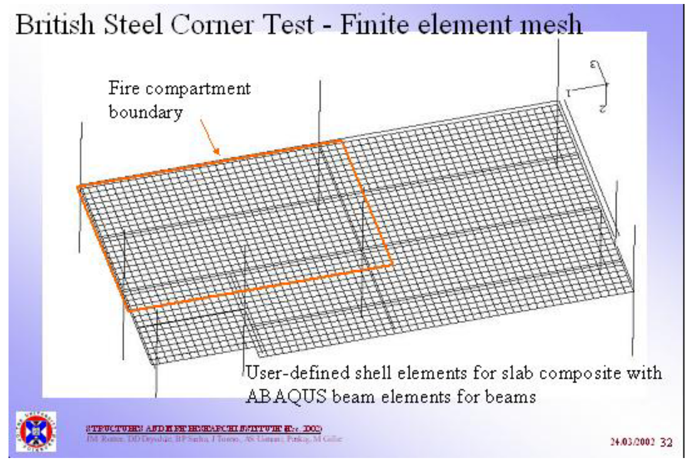

Deflections from generalised stress shell
Deflection of tested beam at mid-span (mm)
model
test
model with no concrete thermal expansion
model with no steel thermal expansion
Temperature of the lower flange of the tested beam (C)
27

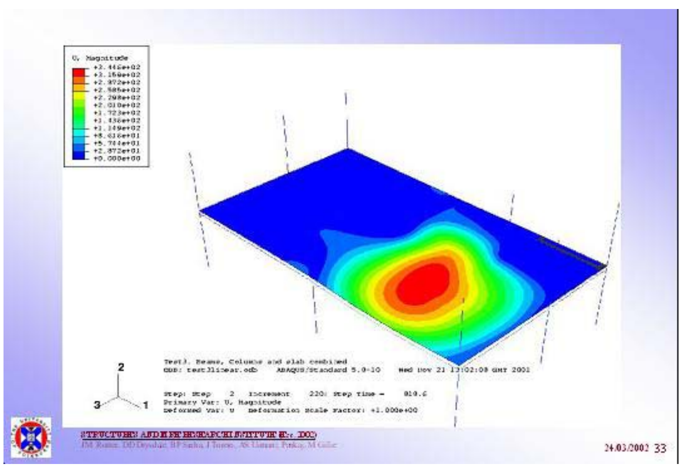

Longitudinal strains at reinf. level
Distance along the primary beam (mm)
Distance along the tested beam (mm)
strain < 0
0.0000 < strain < 0.001
0.001 < strain < 0.002
strain > 0.002
28

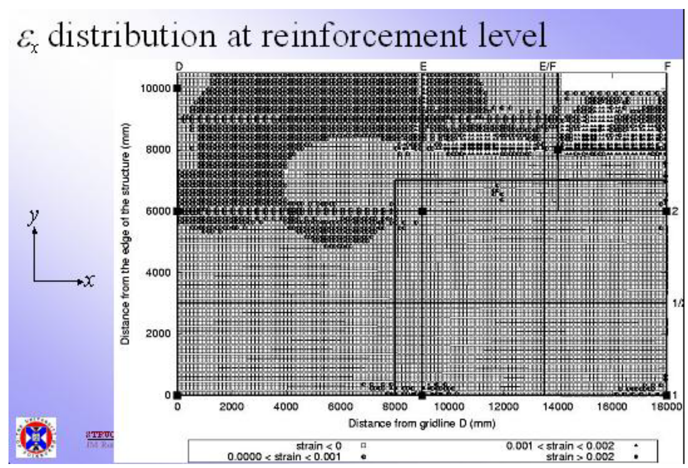

Transverse strains at reinf. level
Distance along the primary beam (mm)
Distance along the tested beam (mm)
strain < 0
0.0000 < strain < 0.001
0.001 < strain < 0.002
strain > 0.002
29

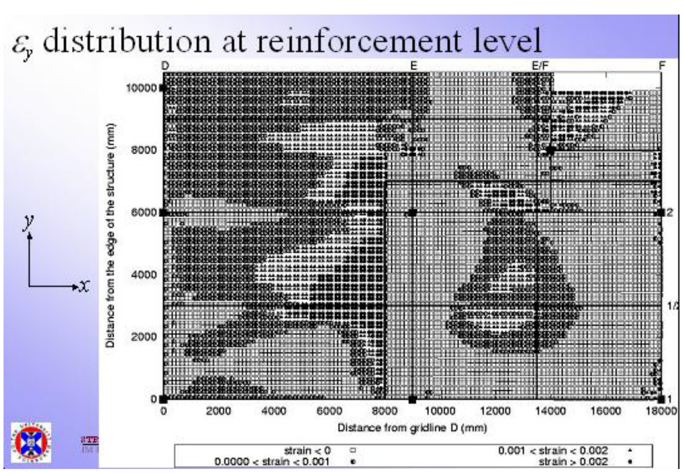

British Steel (now Corus) Corner Test
TEST COMPARTMENT
TEST 3 : CORNER COMPARTMENT TEST
30

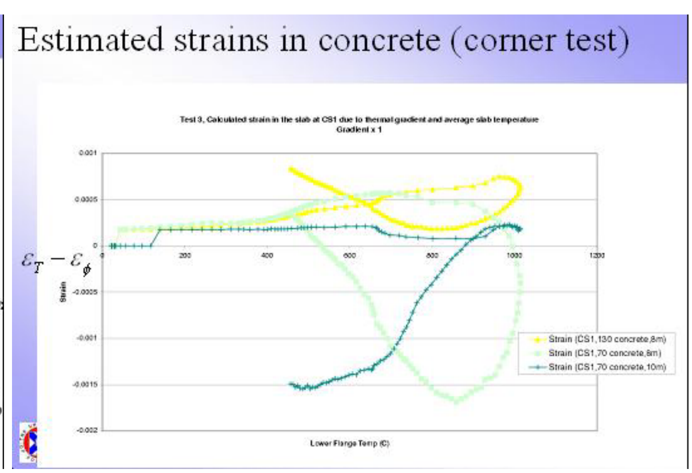

British Steel Corner Test (structure)
Test 3 - Transducer Positions for Measuring Vertical Deflections
31


British Steel Corner Test - Finite element mesh
Fire compartment boundary
User-defined shell elements for slab composite with ABAQUS beam elements for beams
24.03.2002 32

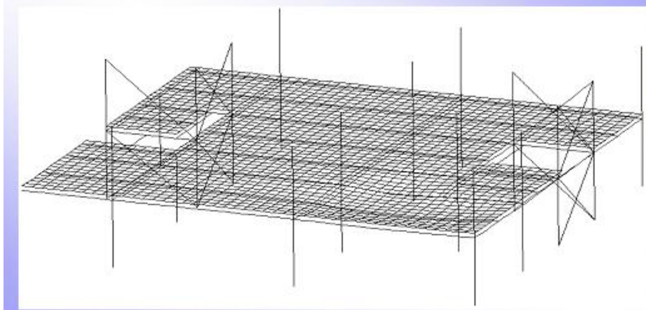

24.03.2002 33


ε_x distribution at reinforcement level
Distance from the edge of the structure (mm)
Distance from gridline D (mm)
strain < 0
0.0000 < strain < 0.001
0.001 < strain < 0.002
strain > 0.002


ε_y distribution at reinforcement level
Distance from the edge of the structure (mm)
Distance from gridline D (mm)
strain < 0
0.0000 < strain < 0.001
0.001 < strain < 0.002
strain > 0.002

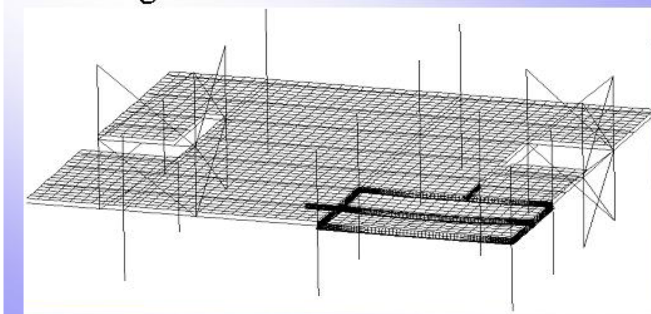

Estimated strains in concrete (corner test)
$\varepsilon_T - \varepsilon_\phi$

Elastic shell model



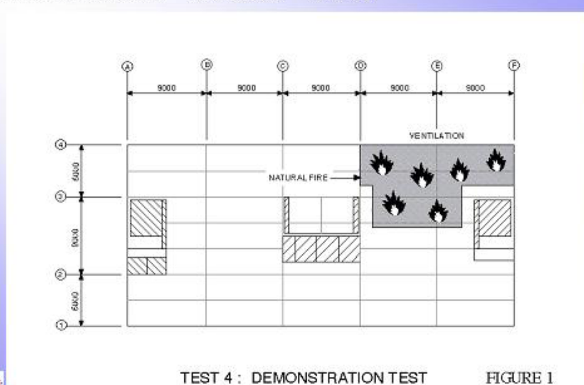
25/03/2002 37

Elastic shell model with detailed beam modelling



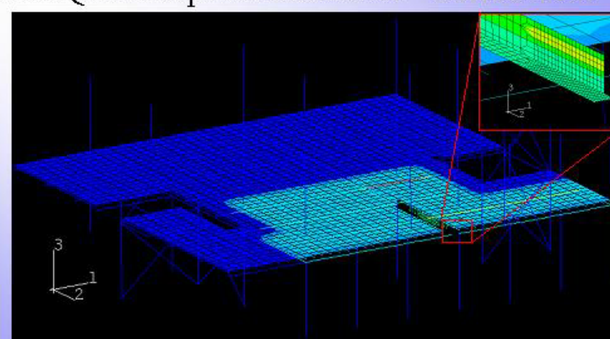
25/03/2002 38

British Steel "Office" Test



002 39

ABAQUS-Explicit model of "Office Test"



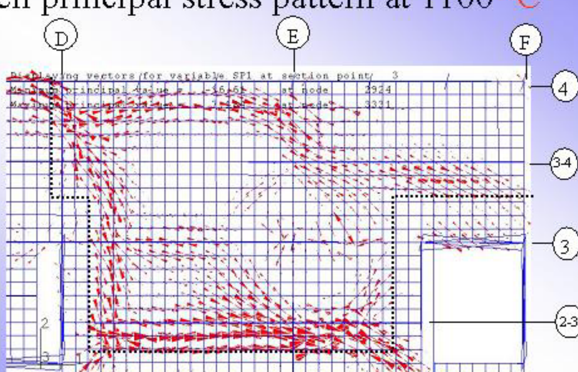
Shown inverted

ABAQUS Concrete cracking model using

Courtesy Corus (STC)

25/03/2002 40

Shell principal stress pattern at 1100 °C



Courtesy Corus (STC)

25/03/2002 41

LESSONS

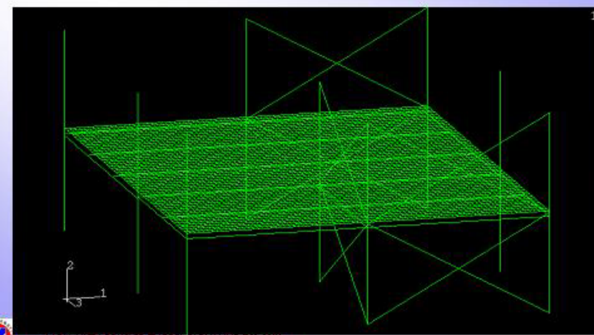
- **Restraint to thermal strains dominates response**
- Conventional loading much less important when restraint is high
- **Response sensitivity to steel strength is low**
- The above will change near failure or collapse, failure not observed in tests of modelling, how far is it?
- **Tensile membrane action (TMA) in the spans and compressive membrane action (CMA) near perimeter observed**
- **This load carrying mechanism more reliable in fire, thermal strains help produce the "right shape"**
- Capacity further enhanced by thermal pre-stressing (CMA)

25/03/2002 42

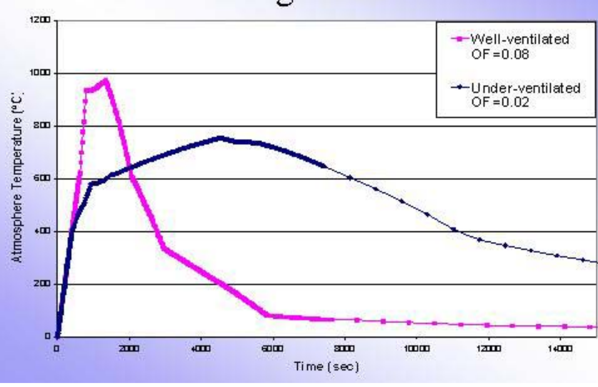
FURTHER MODELLING

- The two key thermal effects governing structural behaviour
  - mean temperature increase => compression => **long cool fires**
  - through depth thermal gradients => tension => **short hot fires**
- Cardington was a medium size braced frame (high redundancy)
  - What about small frames (low redundancy) and whole floor fires
  - What about very large frames (with large compartments)
- Tensile membrane force need anchoring at compartment perimeter
  - Interior continuity can be provided by lapping reinforcement
  - Edge and corner compartments have discontinuous edges
  - Edge beam protection

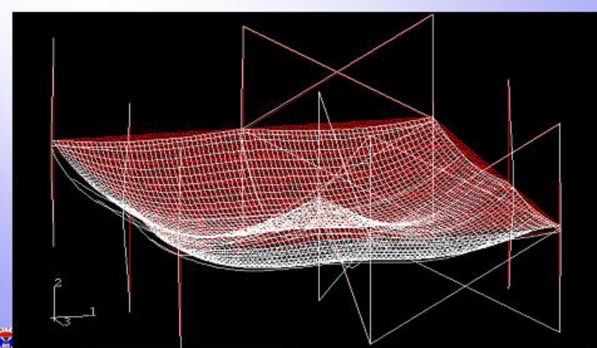
The 2x2 generic frame mesh



Pettersson design fires



The 2x2 generic frame mesh



Studies with different fire scenarios

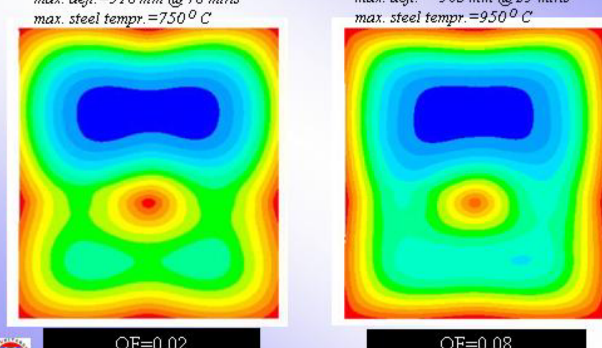
Long-Cool fires
Short-Hot fires

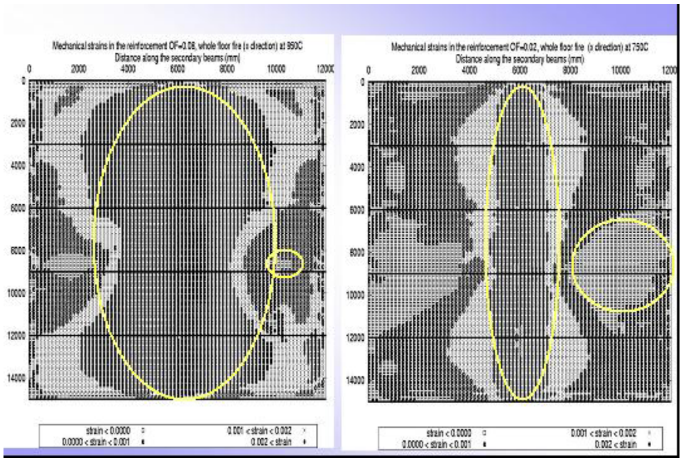
Deflection Contours - 2x2 generic frame

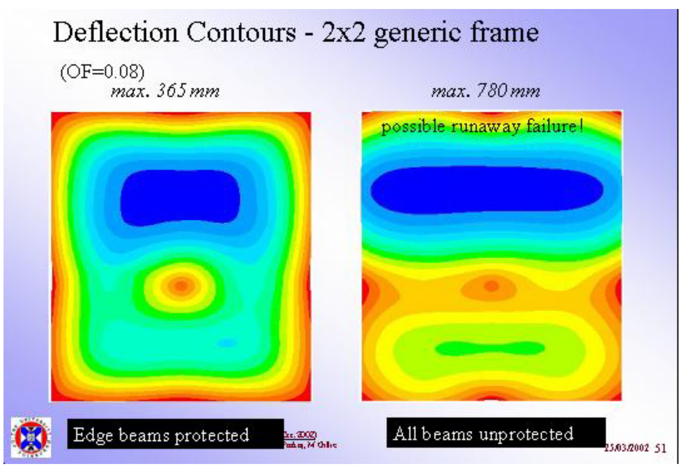
(protected edge beams)

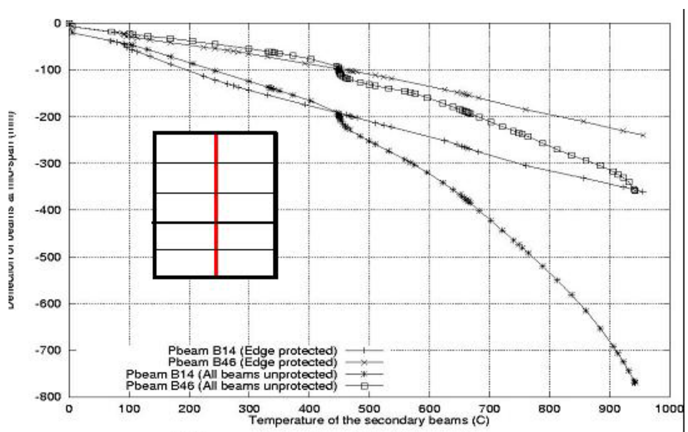
max. defl.=310 mm @ 78 mins
max. steel tempr.=750 ° C

max. defl. = 365 mm @ 23 mins
max. steel tempr.=950 ° C

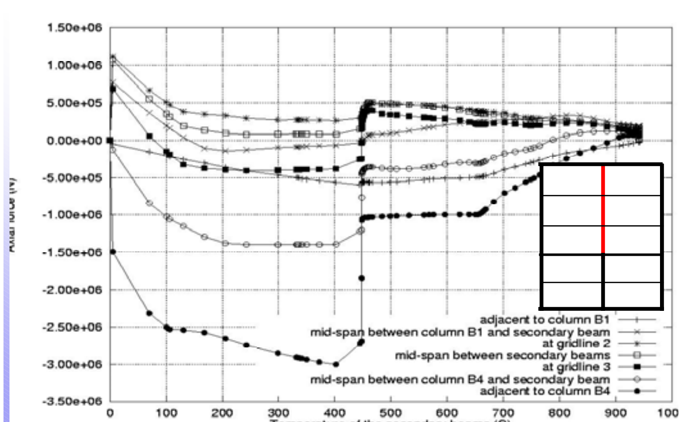




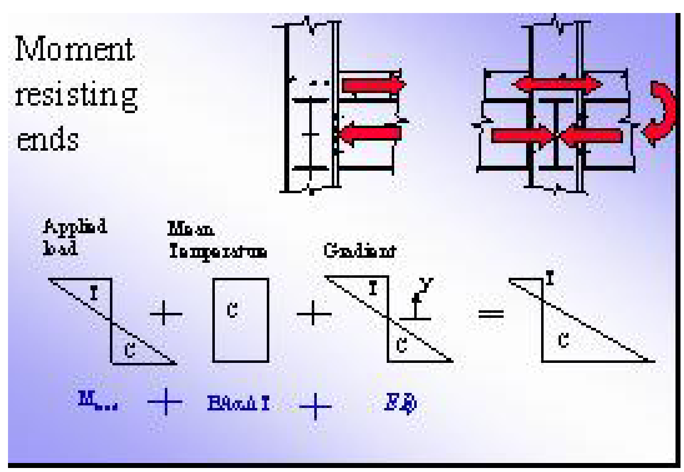


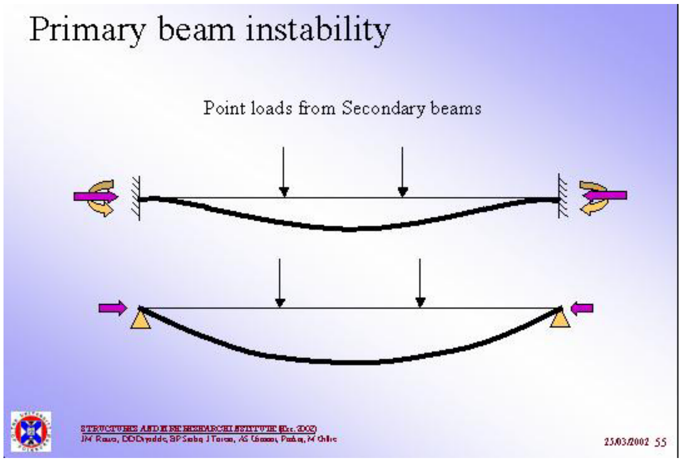


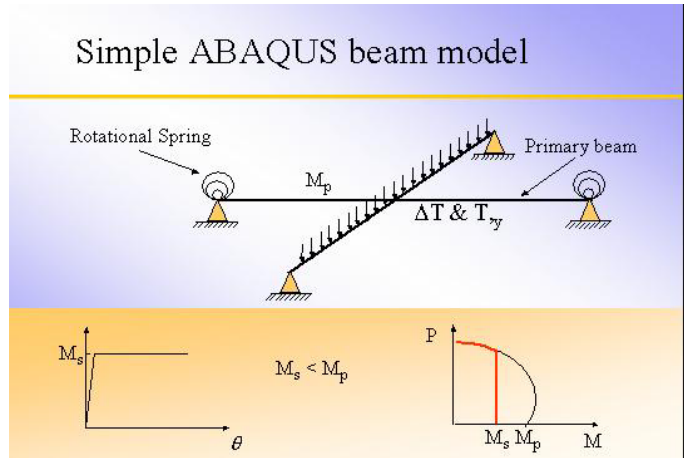
Mid-span deflection of the Primary beams

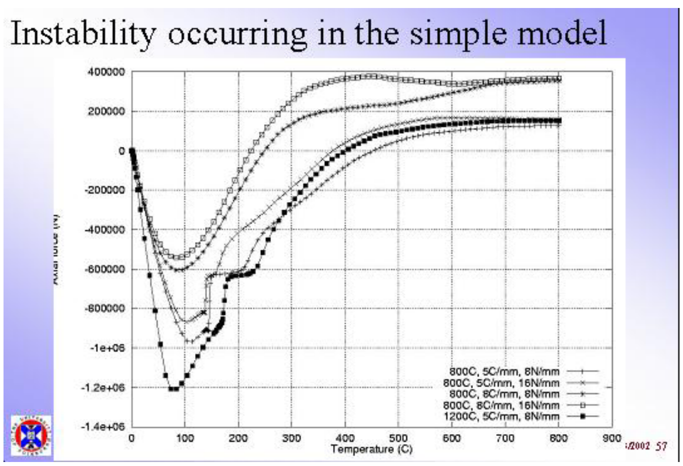


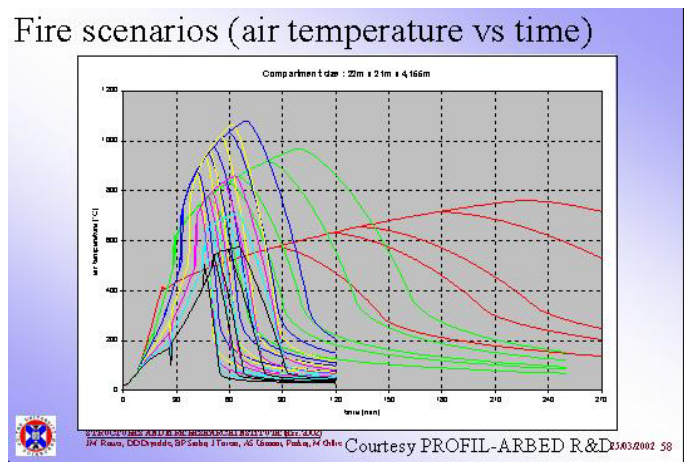
Axial force in primary beam B14: All beams unprotected

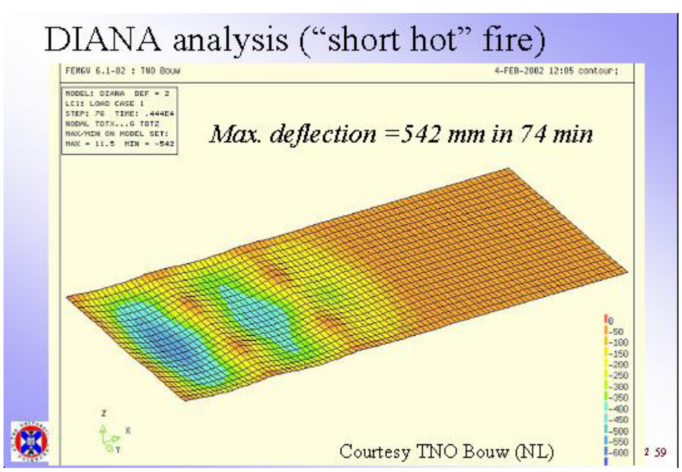


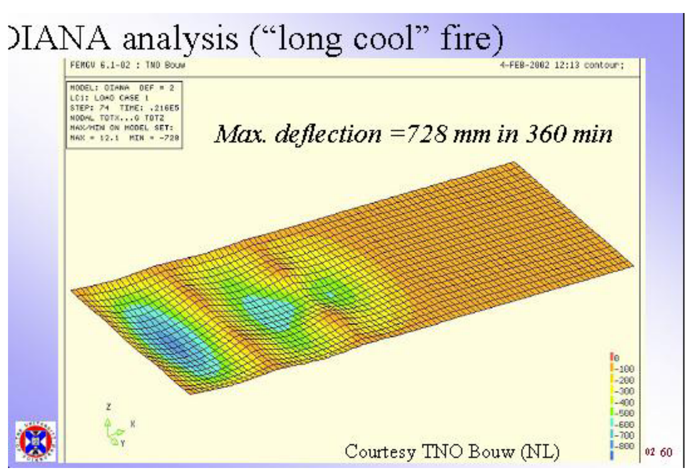

Primary beam instability
Point loads from Secondary beams
25/03/2002 55


Simple ABAQUS beam model
Rotational Spring
Primary beam
Mp
ΔT & T,y
Ms
Ms < Mp
P
θ
Ms Mp
M

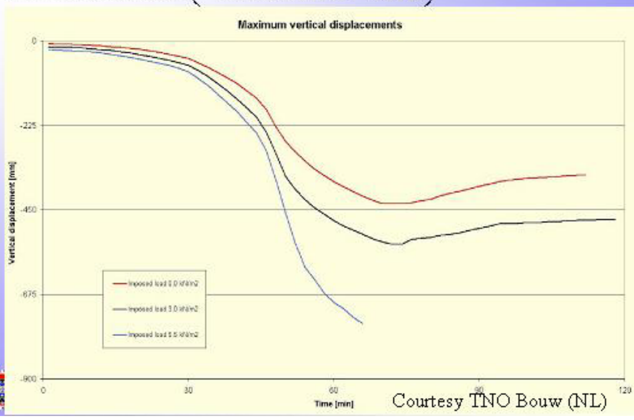

Instability occurring in the simple model
Temperature (C)
800C, 5C/mm, 8N/mm
800C, 5C/mm, 16N/mm
800C, 8C/mm, 8N/mm
800C, 8C/mm, 16N/mm
1200C, 5C/mm, 8N/mm


Fire scenarios (air temperature vs time)
Courtesy PROFIL-ARBED R&D
25/03/2002 58

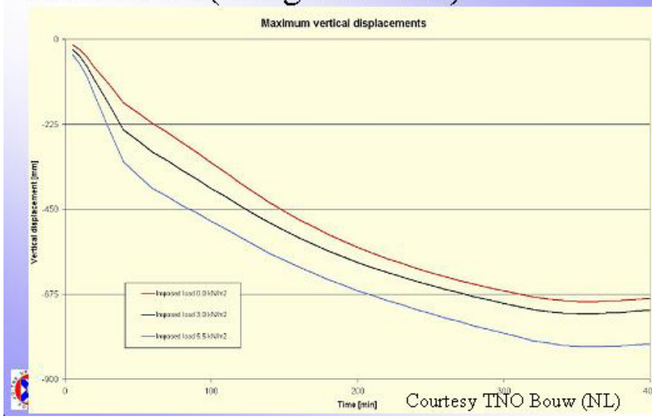

DIANA analysis ("short hot" fire)
Max. deflection =542 mm in 74 min
Courtesy TNO Bouw (NL)


DIANA analysis ("long cool" fire)
Max. deflection =728 mm in 360 min
Courtesy TNO Bouw (NL)

Deflections ("short hot" fire)



Deflections ("long cool" fire)



Conclusions

- Fire design is based on time - Structural response depends on temperature and rate of heating
  - Implications of this on current thinking?
- Different fires can produce very different very different stress/strain patterns in composite floor systems
- The benefit of protecting edge beams seems worthwhile (to enable anchorage of membrane forces and "tying" effect - also cladding protection)
- A new (and possibly dynamic) phenomenon identified which needs confirmation and assessment of it potential for damage

Further research: Strategic

- **Worst case fire scenario can only be based on its potential for structural damage** (only for structural integrity considerations)
- Limit state design scenarios must be the basis of all structural design
- **Limit states resulting from extreme fire events should be included**
- Localised collapse should not cause over all progressive collapse
- **Tall buildings (where suppression/evacuation time is large), will require special consideration (no collapse)**

Further research: issues of detail

- **Floor slab failures, are they ductile (runaway) or brittle (fracture)**
- **Short hot v Long cool fires: which is worse?**
- What happens on cooling?
- Detailed modelling of connections
- What kind of fire loading in large compartments
- Integrity of non-loadbearing compartment boundaries
- Development of a rational restrained test
- **HOW TO DEFINE FAILURE?**

25/03/2002 65

http://www.civ.ed.ac.uk/research/fire/project/main.html

25/03/2002 66