Effect of Unprotected Interior Beams on Membrane Behaviour of Composite Floor Systems in Fire

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Content

- Benchmarking numerical models
- Literature review on Membrane Behaviour of Composite Slabs in fire
- Objectives
- Test Setup
- Test Results
- Finite Element Analysis
- Discussions
- Conclusion

Literature | Objectives | Test setup | Test results | FE analysis | Discussions | Conclusion

Benchmarking numerical models

- Limitations of structural tests, scaling effect, objective of tests, boundary conditions, and loading
- Modelling thermal response – such as radiation, convection and conduction
- Structural behaviour:
  - Sensitivity of mesh study
  - choice of finite elements
  - Loading conditions
  - Use of symmetry
- Material behaviour:
  - Range of possible values

Benchmarking numerical models

- Motivations of numerical modeling
  - Understanding the limitations of numerical modelling
  - Test measurements are not continuous
  - Details of stresses and strains at interesting locations are not measured
  - Complex interactions between various components (beams, slabs and columns) cannot be known
  - Triggering sources of failure cannot be clearly observed
  - Failure criteria
  - Collapse mechanisms cannot be clearly defined

Benchmarking numerical models

- Illustration through two physical tests
- Illustration through numerical models
- Comparison of numerical models with physical tests
- Key parameters in composite slab behaviour
  - Effect of leaving interior beams unprotected;
  - Rotational edge-restraint;
  - Bending stiffness of protected main and secondary edge beams;
  - Vertical deflection of protected edge beams;
- Usefulness of numerical modeling
  - Identify key parameters that influence overall behaviour
  - Perform parametric studies
  - Lead to development of design guide

Brief history of testing on composite slabs in fire

Six full-scale tests conducted at Cardington by BRE

1995-1996

Cardington fire tests

1. Tests on isolated slab panels
2. Thermal/structural programs
3. Analytical models
4. Design guide in UK

2000 - 2007

Bailey CG and Moore DB (2000)
Huang *et al.* (2000) – VULCAN
Foster *et al.* (2004)
Bailey Foster *et al.* (2004)
Izzuddin BA and Elghazouli AY (2004)
Cameron NJK and Usmani AS (2005)
Franssen JM (2005) – SAFIR
SCI P288 (Newman GM *et al*. 2006)
ADAPTIC software

1. New interest on testing of the floor assemblies in fire
2. Design guides outside UK

2008 - present

Fracof test (2008)
Zhang NS and Li GQ (2009)
Mokrsko fire test (2009)
Stadler M. *et al.* (2011) – Munich tests
Wellman E *et al.* (2011)
Nguyen TT and Tan KH (2012)

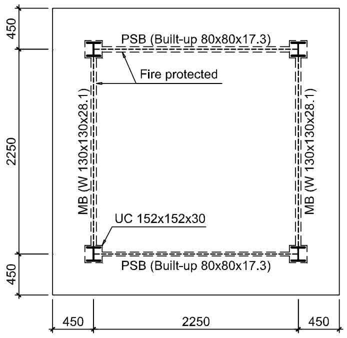
Only a few key references are mentioned!

Literature Objectives Test setup Test results FE analysis Discussions Conclusion

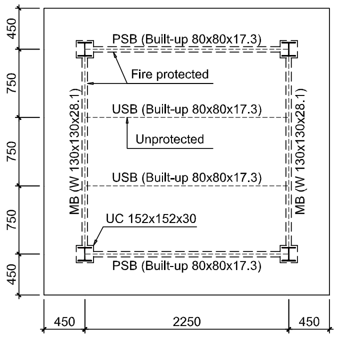
Experimental Program
Objectives

- Study the effects of some important parameters on the membrane behaviour of composite floor assemblies under fire conditions
  - Effect of leaving interior beams unprotected;
  - Rotational edge-restraint;
  - Bending stiffness of protected main and secondary edge beams;
  - Vertical deflection of protected edge beams;
- Capture failure modes and deformed shapes of the composite beam-slab systems;
- Validate the proposed nonlinear FE models;

Experimental Program
Series I – 3 specimens



S1 & S3-FR

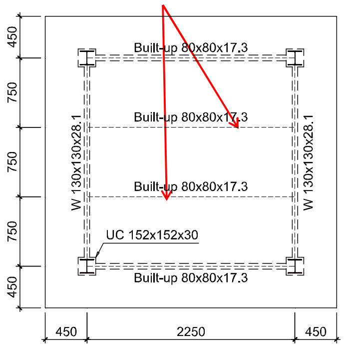


S2-FR-IB

- Specimen S1 had the same configuration as S3-FR, but its test setup was different.
- S1 had no rotational restraint beam system on top of the outstands, while S3-FR had. The aim is to study the effect of rotational restraint on the behaviour of beam-slab systems.

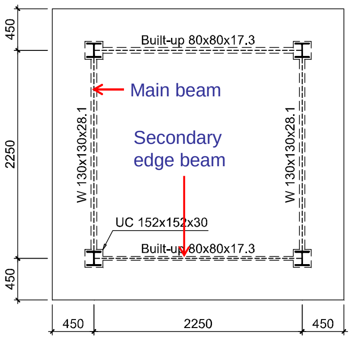
Test results of two specimens, S2-FR-IB and S3-FR, are presented.

Two unprotected interior beams



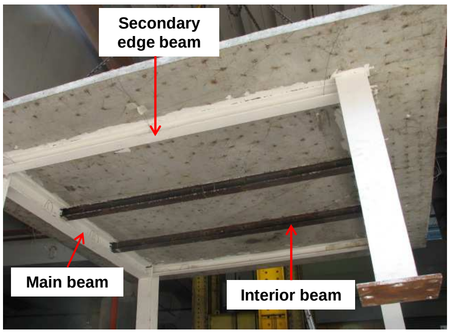
S2-FR-IB

Without any interior beam

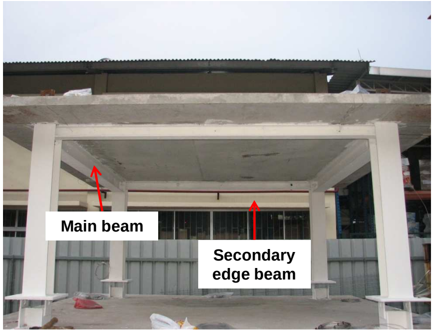


S3-FR

Shrinkage reinforcement mesh, 80mm x 80mm grid size and 3mm diameter, was placed within the slabs at 18mm from the top.



S2-FR-IB

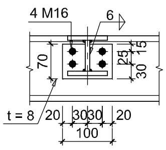


S3-FR

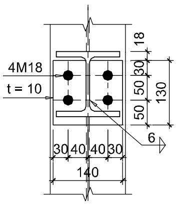
The columns, secondary edge beams(PSB) and main beams (MB) were protected to a prescriptive fire rating of 60min.

Flexible end plate connections were used.

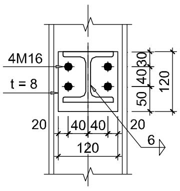
BEAM-TO-BEAM



MB-TO-COLUMN

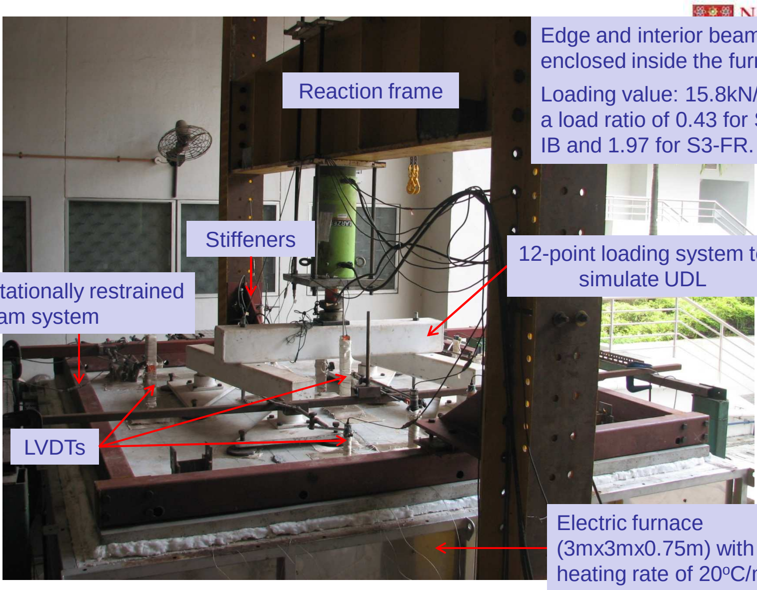


PSB-TO-COLUMN



Tab. 1 Properties of I-beams

Specimen		Depth h (mm)	Width b_f(mm)	Thickness Web t_w (mm)	 Flange t_f (mm)	Yield stress f_y (MPa)	Ultimate stress f_u (MPa)	Elastic modulus E_s (MPa)
S2-FR-IB	MB	131	128	6.96	10.77	302	437	197500
	PSB & USB	80	80	9.01	9.14	435	533	206900
S3-FR	MB	131	128	6.97	11.03	307	462	211364
	PSB & USB	80	80	10.26	10.02	467	588	210645



Edge and interior beams were enclosed inside the furnace.

Loading value: 15.8kN/m^2 ≈ a load ratio of 0.43 for S2-FR-IB and 1.97 for S3-FR.

‘Failure’ definition

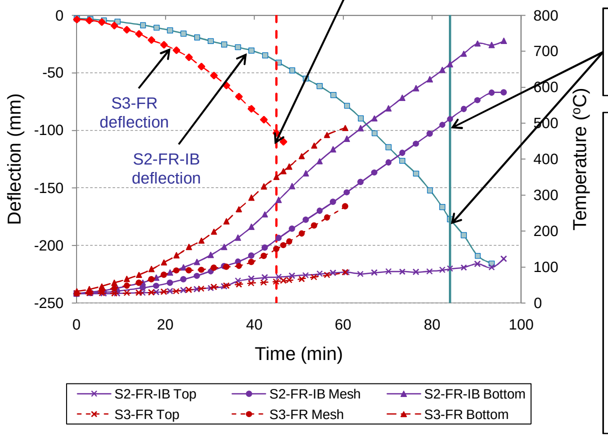
‘Failure’ was defined as the time when either:

(1) Appearance of full-depth cracks (integrity criterion “*E*”)

(2) Significant drop in the mechanical resistance -> the jack could no longer maintain the load level (load-bearing criterion “*R*”)

Temperature Development Slab Deflection

S3-FR failed earlier at 115mm and at a mesh temperature of 150°C

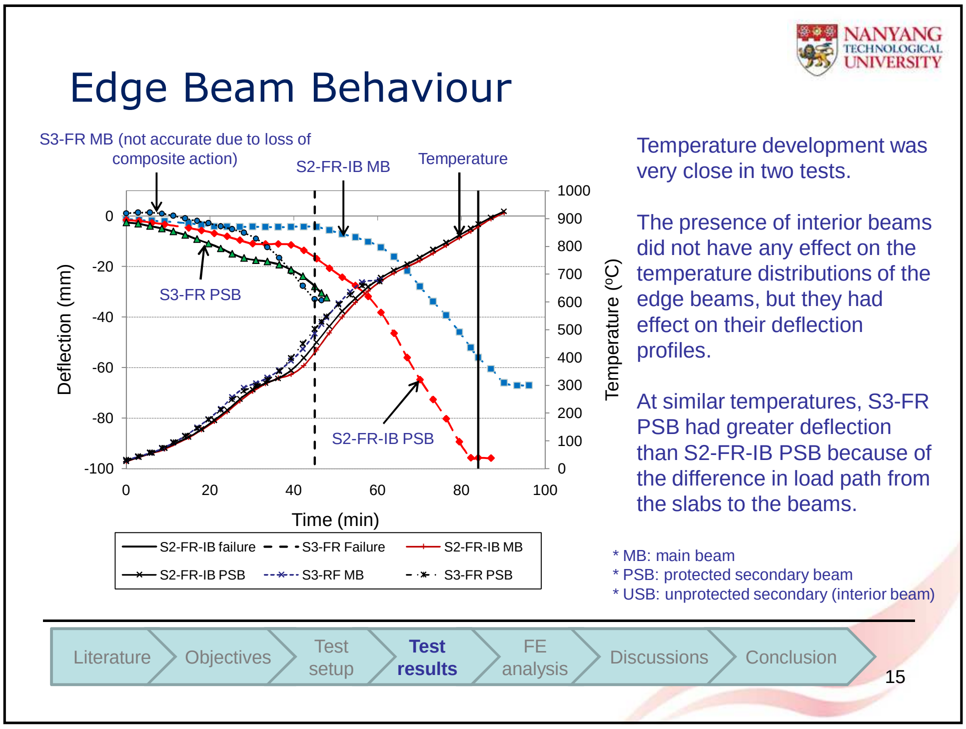


S2-FR-IB failed at 177mm and at a mesh temperature of 512°C

S3-FR (no interior beam) experienced larger deflection than S2-FR-IB, and failed sooner.

Enhancement factor: 2.55 (S2-FR-IB) > 1.54 (S3-FR)

Leaving interior beam unprotected did not affect temperature distribution of the edge beams.



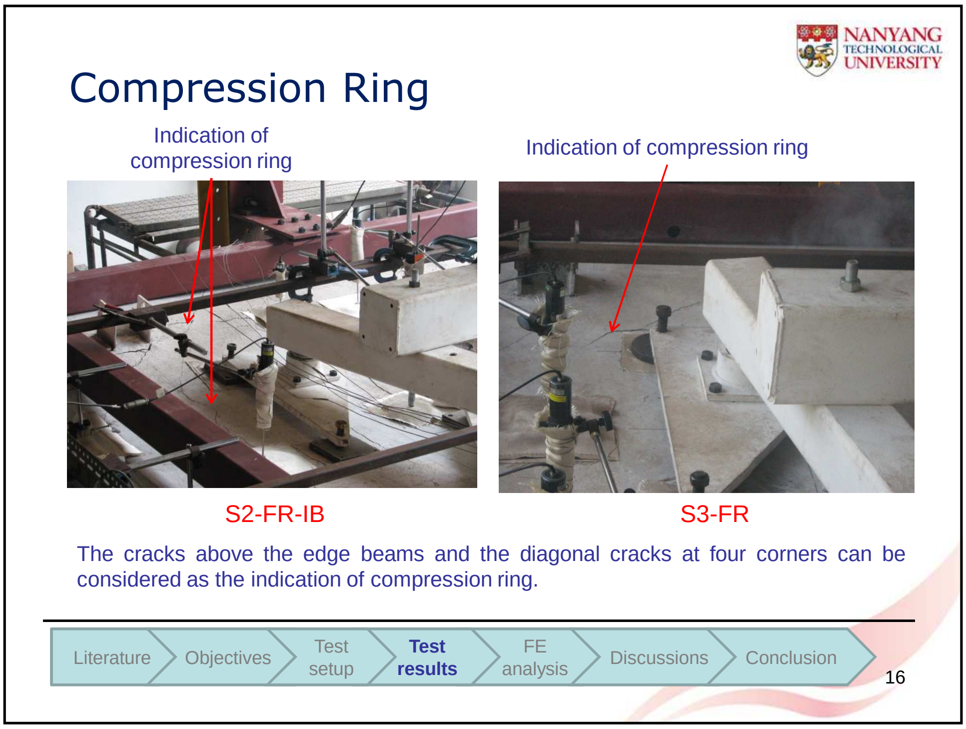
Edge Beam Behaviour

Temperature development was very close in two tests.

The presence of interior beams did not have any effect on the temperature distributions of the edge beams, but they had effect on their deflection profiles.

At similar temperatures, S3-FR PSB had greater deflection than S2-FR-IB PSB because of the difference in load path from the slabs to the beams.

* MB: main beam
* PSB: protected secondary beam
* USB: unprotected secondary (interior beam)



Compression Ring

S2-FR-IB

S3-FR

The cracks above the edge beams and the diagonal cracks at four corners can be considered as the indication of compression ring.

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Compression Ring

- S2-FR-IB: compression ring formed at 200ºC (mesh temperature) and at 52mm, 0.95 of the slab depth, after 50min of heating.
- S3-FR: compression ring formed at 100ºC (mesh temperature), and at 52mm, equal to 0.95 of the depth, after 30min of heating.

-> The compression ring formed at the slab deflection equal to about 1.0 of the slab thickness, irrespective of the presence of interior beams.

- S2-FR-IB (with interior beams) entered TMA later than S3-FR, because the unprotected interior beams enhanced the slab capacity during the bending stage.

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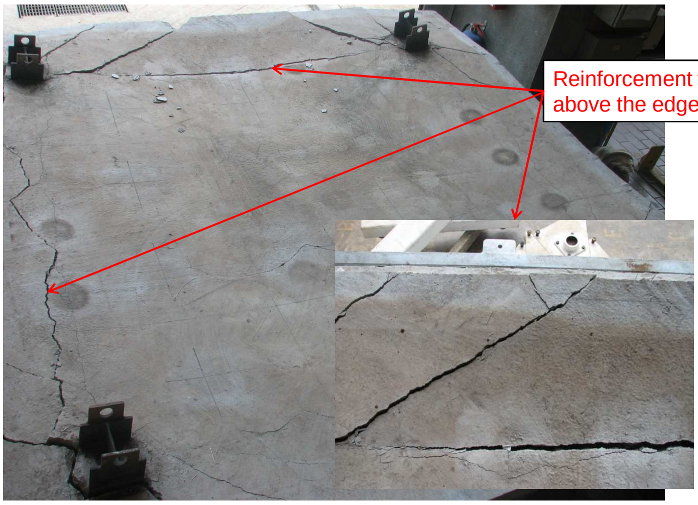
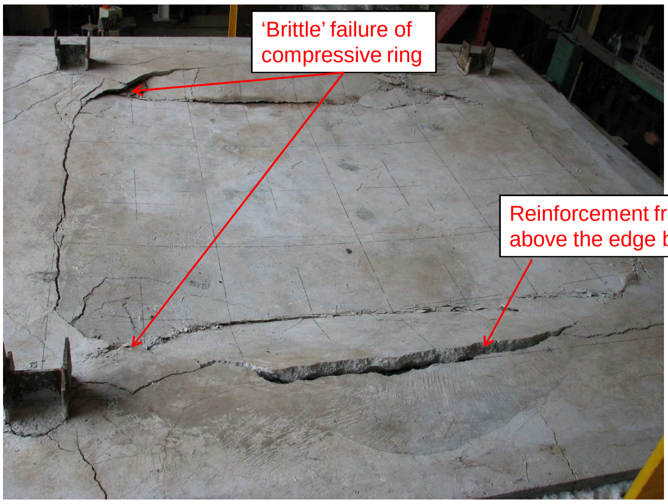
Failure Modes: S2-FR-IB



Reinforcement fracture above the edge beams

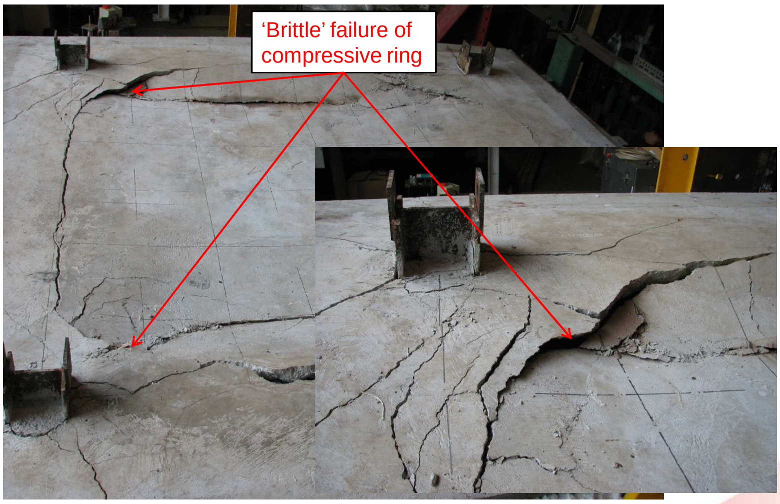
Failure Modes: S3-FR



'Brittle' failure of compressive ring

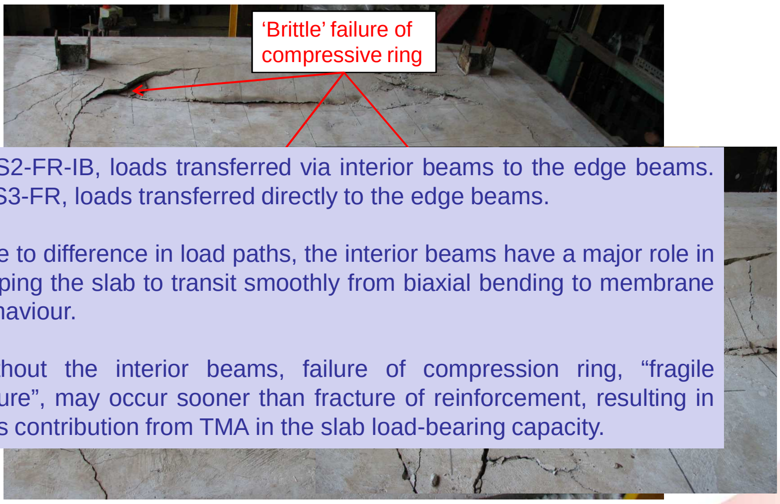
Reinforcement fracture above the edge beams

Failure Modes: S3-FR



'Brittle' failure of compressive ring

Failure Modes: S3-FR

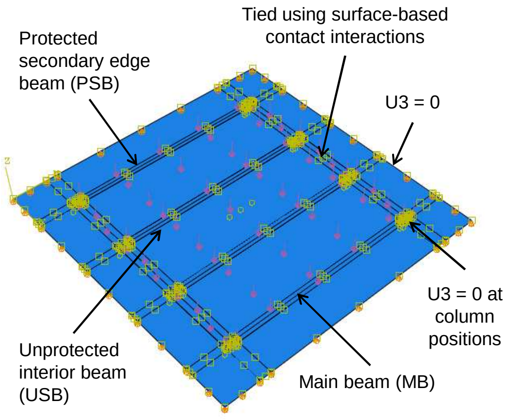


In S2-FR-IB, loads transferred via interior beams to the edge beams. In S3-FR, loads transferred directly to the edge beams.

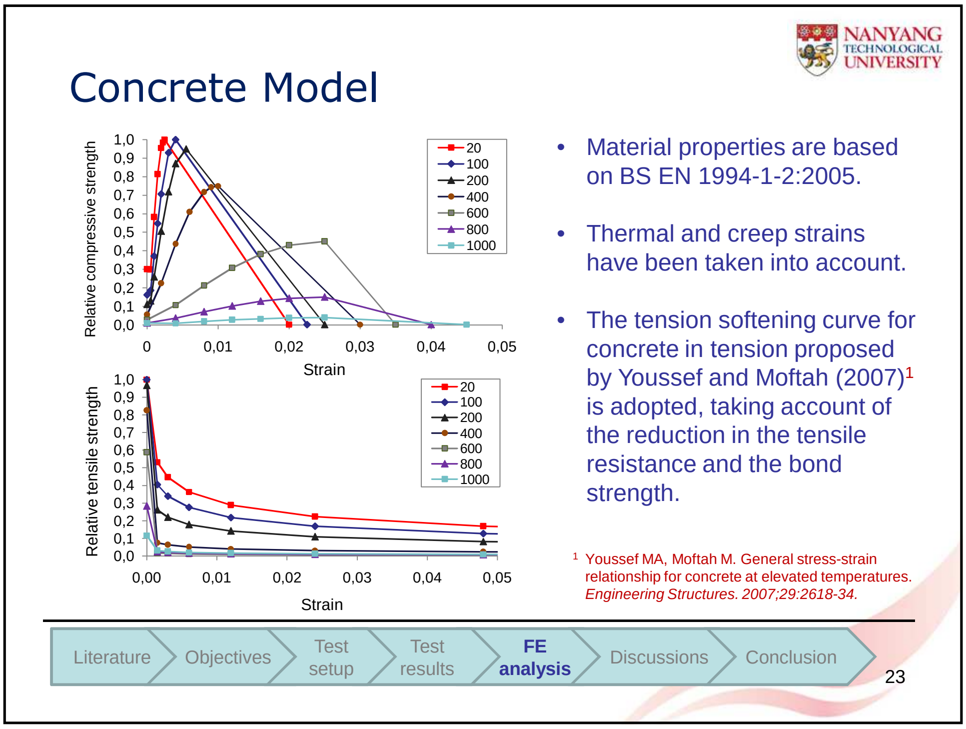
Due to difference in load paths, the interior beams have a major role in helping the slab to transit smoothly from biaxial bending to membrane behaviour.

Without the interior beams, failure of compression ring, "fragile failure", may occur sooner than fracture of reinforcement, resulting in less contribution from TMA in the slab load-bearing capacity.

Proposed Nonlinear FE model



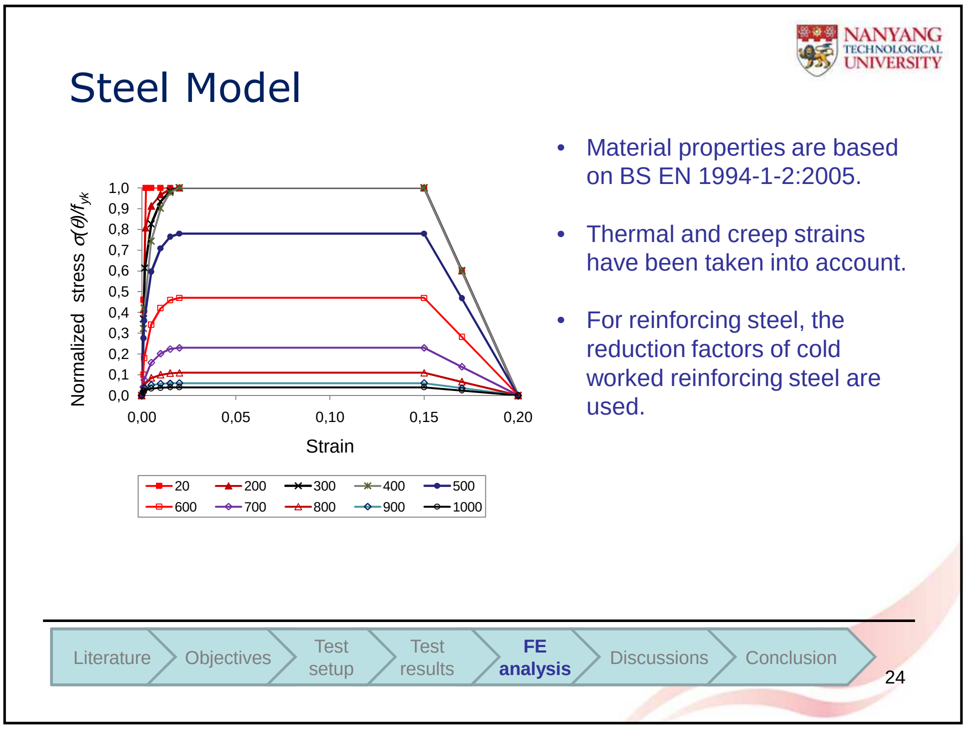
- ABAQUS/Explicit
- Sequentially coupled thermal-stress analysis procedure
- Shell element type S4R
- Concrete Damaged Plasticity Model & Rebar layer technique
- Temperature at the slab bottom surface was input directly into the model to define thermal gradient over the slab thickness.



Concrete Model

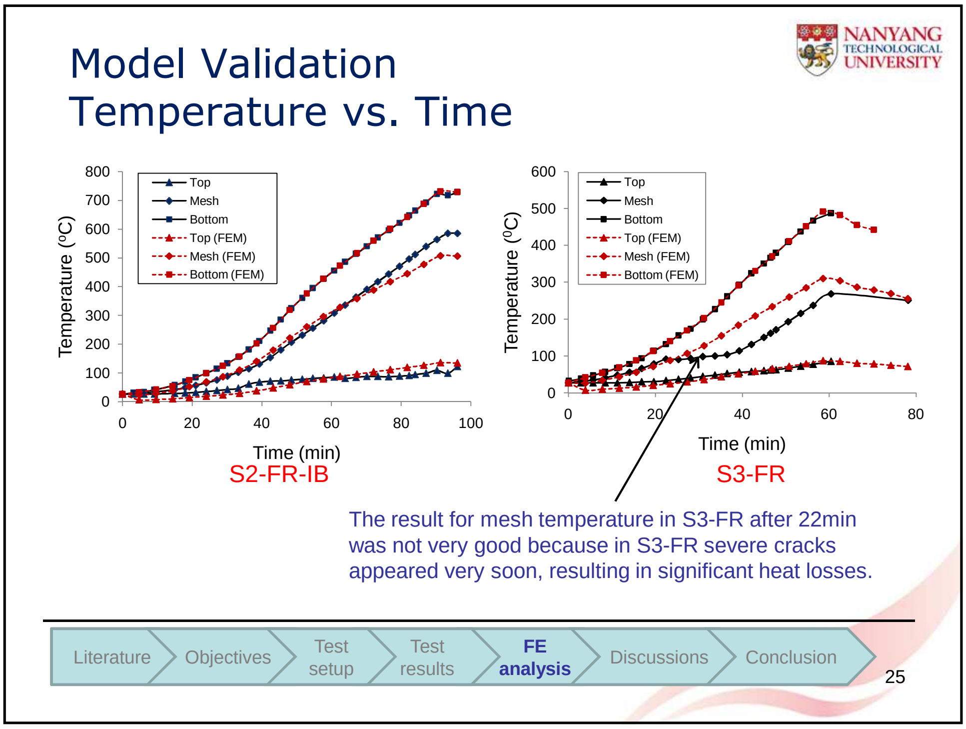
- Material properties are based on BS EN 1994-1-2:2005.
- Thermal and creep strains have been taken into account.
- The tension softening curve for concrete in tension proposed by Youssef and Moftah (2007)[1] is adopted, taking account of the reduction in the tensile resistance and the bond strength.

[1] Youssef MA, Moftah M. General stress-strain relationship for concrete at elevated temperatures. *Engineering Structures. 2007;29:2618-34.*



Steel Model

- Material properties are based on BS EN 1994-1-2:2005.
- Thermal and creep strains have been taken into account.
- For reinforcing steel, the reduction factors of cold worked reinforcing steel are used.

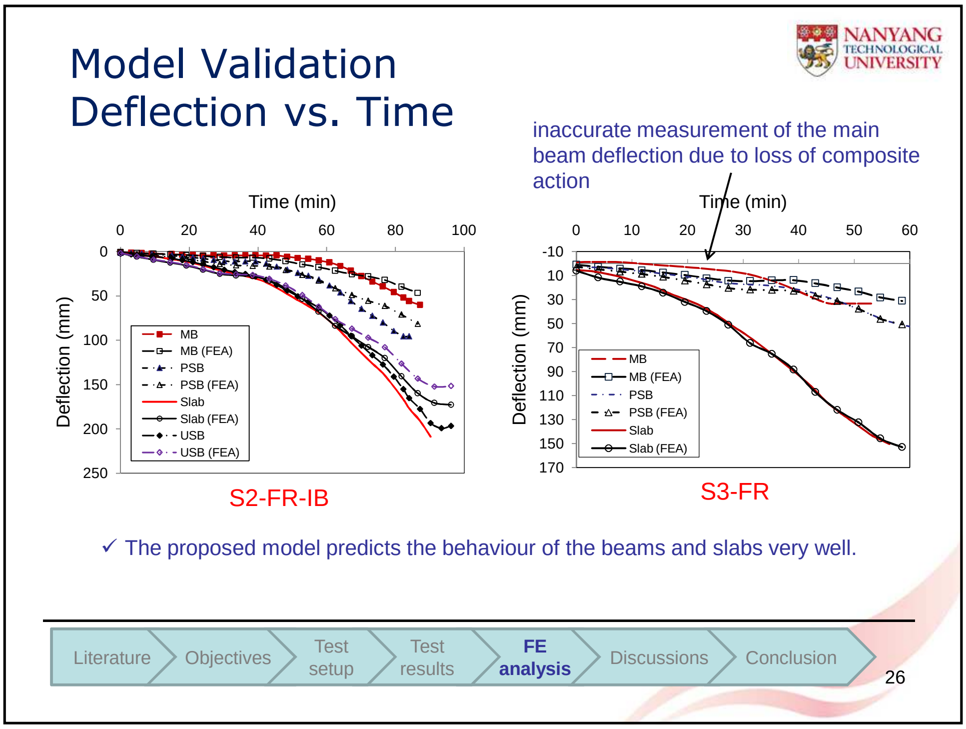


Model Validation
Temperature vs. Time

S2-FR-IB

S3-FR

The result for mesh temperature in S3-FR after 22min was not very good because in S3-FR severe cracks appeared very soon, resulting in significant heat losses.



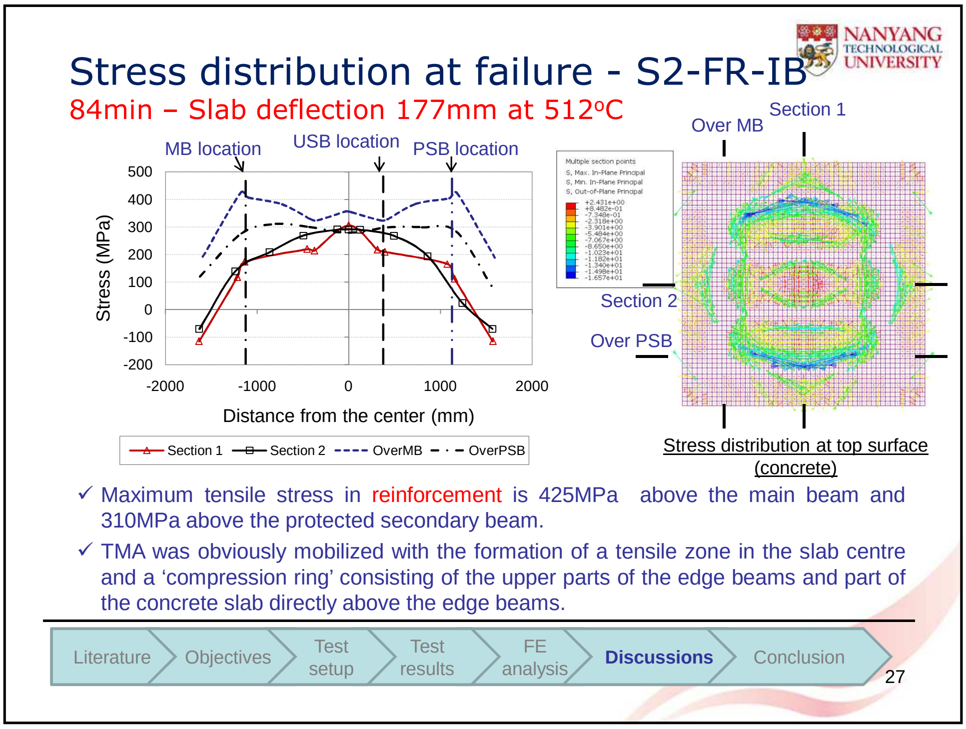
Model Validation
Deflection vs. Time

inaccurate measurement of the main beam deflection due to loss of composite action

S2-FR-IB

S3-FR

✓ The proposed model predicts the behaviour of the beams and slabs very well.



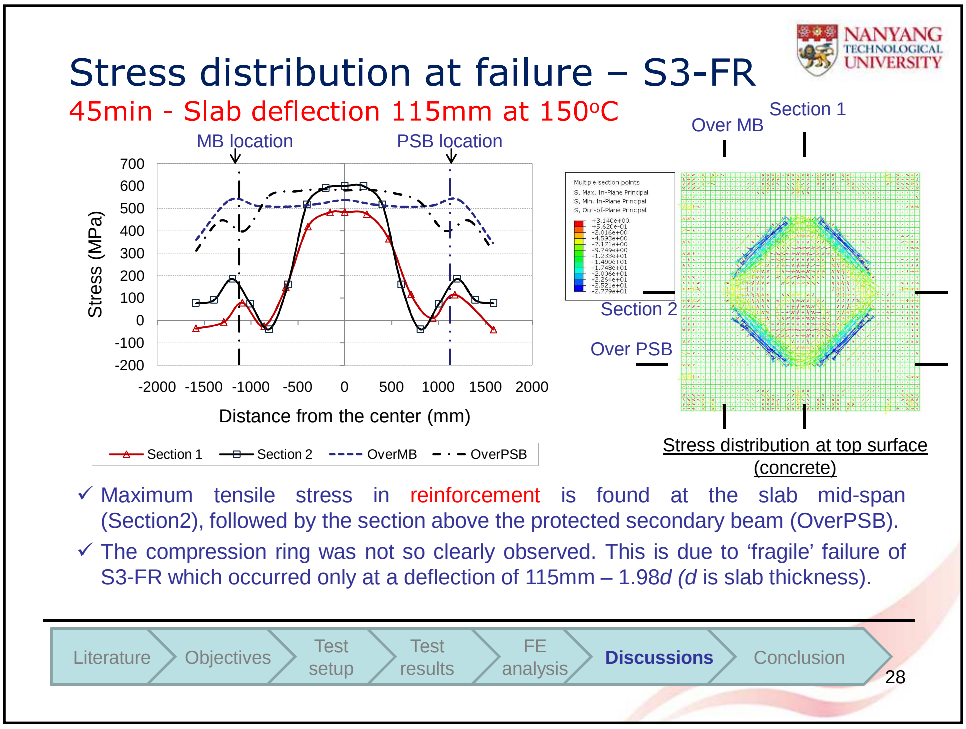
Stress distribution at failure - S2-FR-IB

84min – Slab deflection 177mm at 512°C

Stress distribution at top surface (concrete)

- ✓ Maximum tensile stress in reinforcement is 425MPa above the main beam and 310MPa above the protected secondary beam.
- ✓ TMA was obviously mobilized with the formation of a tensile zone in the slab centre and a 'compression ring' consisting of the upper parts of the edge beams and part of the concrete slab directly above the edge beams.

Literature | Objectives | Test setup | Test results | FE analysis | **Discussions** | Conclusion



Stress distribution at failure – S3-FR

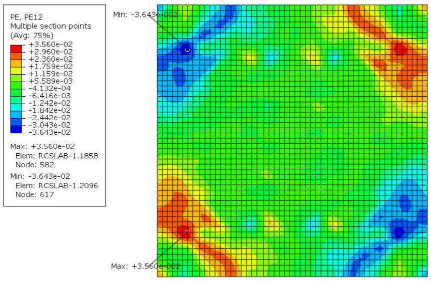
45min - Slab deflection 115mm at 150°C

Stress distribution at top surface (concrete)

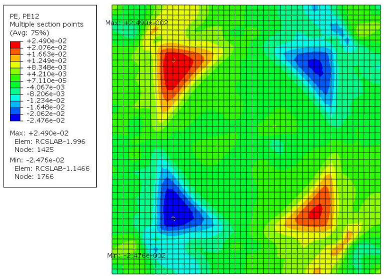
- ✓ Maximum tensile stress in reinforcement is found at the slab mid-span (Section2), followed by the section above the protected secondary beam (OverPSB).
- ✓ The compression ring was not so clearly observed. This is due to 'fragile' failure of S3-FR which occurred only at a deflection of 115mm – 1.98*d* (*d* is slab thickness).

Literature | Objectives | Test setup | Test results | FE analysis | **Discussions** | Conclusion

Strain distribution at top surface at failure



S2-FR-IB



S3-FR

- ✓ Maximum strain of concrete at the corners is 0.0356 and 0.0249 for S2-FR-IB and S3-FR, respectively.
- ✓ These values are higher than the failure compressive strain according to EN 1994-1-2, which are 0.0223 for S2-FR-IB and 0.0213 for S3-FR at the same temperature.
- ✓ It means that at the slab corners, the stress in concrete top surface is almost zero, or failure would occur in these regions.

Failure modes

On the basis of numerical simulations:

- In S2-FR-IB test, reinforcement fracture above the edge beams would occur first, before reinforcement fracture at the slab mid-span. This failure mode concurs with the experimental observations.
- In S3-FR, failure is predicted to be due to fracture of reinforcement at the slab mid-span. Based on the maximum compressive strain of S3-FR, failure would also occur in the slab corners.
- Unfortunately, there is no obvious indication of which failure mode, i.e. reinforcement fracture at the slab mid-span or concrete crushing at the slab corner, would occur first.

Shortcomings of the numerical model

- Final failure modes of the beam-slab substructures could not be exactly identified from the stress or strain contours.
- Partial failures such as concrete crushing and fractures of rebars can not be taken into account.
- Heat loss caused by the appearance of concrete cracks could not be predicted.

Literature Objectives Test setup Test results FE analysis **Discussions** Conclusion

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Conclusions

1. Understanding the limitations of numerical modelling
2. Details of stresses and strains at interesting locations
3. Complex interactions between various components (beams, slabs and columns)
4. Failure criteria
5. Collapse mechanisms

Literature Objectives Test setup Test results FE analysis Discussions **Conclusion**

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Conclusions

1. The presence of interior beams greatly enhances the load-bearing capacity of the slab.
    - ✓ S3-FR failed sooner with higher deflection (Slide 10);
    - ✓ In term of enhancement factor, S2-FR-IB has a greater enhancement factor (2.55) compared to 1.54 of S3-FR;
2. Without interior beams, the slab may experience 'brittle' failure of the compression ring and caused 'run-away' failure in the slab.
3. The compression ring formed at the slab deflection equal to 0.95 of the slab thickness, irrespective of the presence of interior beams.
4. The presence of interior beams significantly affects the magnitude as well as the distribution of stresses in the slab elements. This may cause different failure modes for the floor assemblies compared with those of isolated slab panels.

Literature > Objectives > Test setup > Test results > FE analysis > Discussions > **Conclusion**

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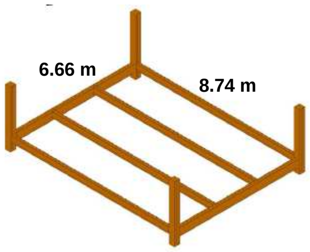
Thank you for your attention!

Validation with Fracof test

***FRACOF fire test* [5]**



a- View over the steel frame


a- at the beginning of fire test
b- at the end of fire test

Fig. 19 – State of slab around steel column

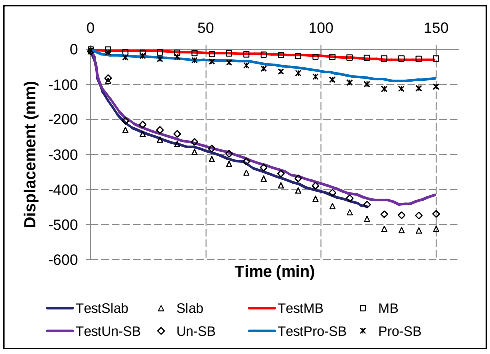

a- State of the cracking at central part of the floor
b- State of the cracking after cooling

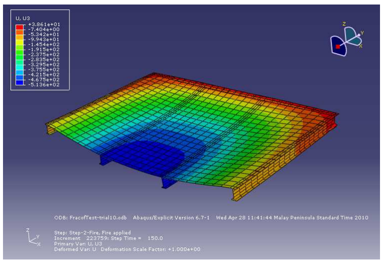
Fig. 20 – State of slab at central part of the floor during and after the test

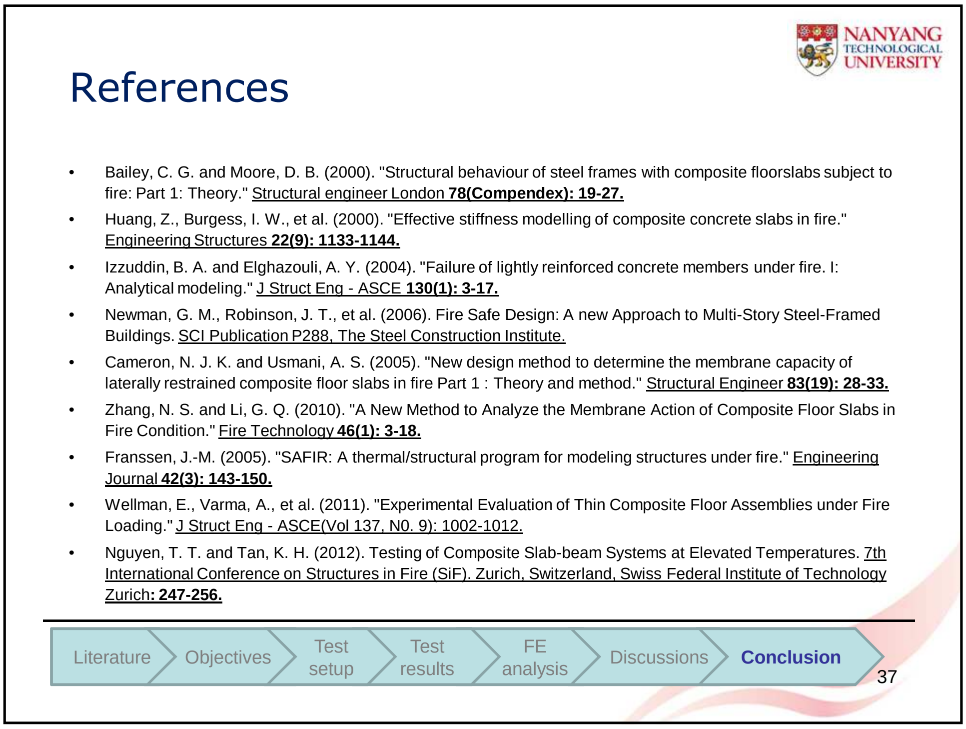
[5] Zhao, B., M. Roosefid, et al. (2008). Full scale test of a steel and concrete composite floor exposed to ISO fire. SiF'08, Singapore, NTU.

Validation with Fracof test

Time- deflection curves at the mid point of the members







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