FiSAC | Fire Safety Asia Conference Singapore 2014

Fire Safety & Emergency Management: The Way Forward

**Professor Tan Kang Hai**

**Director of MINDEF-Protective Technology Research Centre**

**School of CEE, Nanyang Technological University**

# "A Safe and Economical Design of Composite Profile Steel Decking Systems under Fire Conditions"

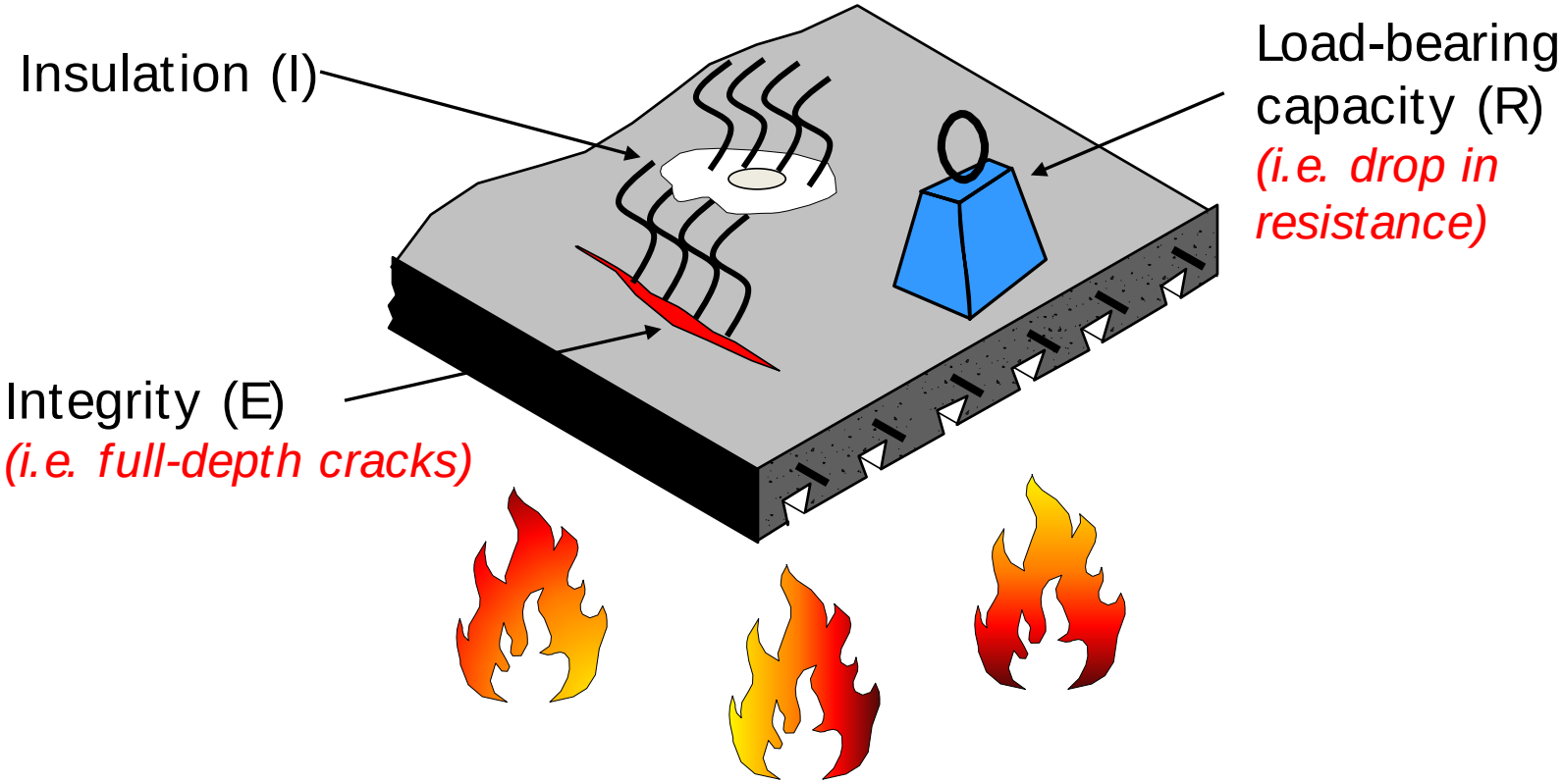
# Contents

- Fire design methods
- Estimation of cost saving for fire-protection
- SCI Publications P288 & P390
- Design Commentary and Calibration of P288 & 390 against NTU fire tests
- Conclusions

# Fire design methods

## Failure Criteria

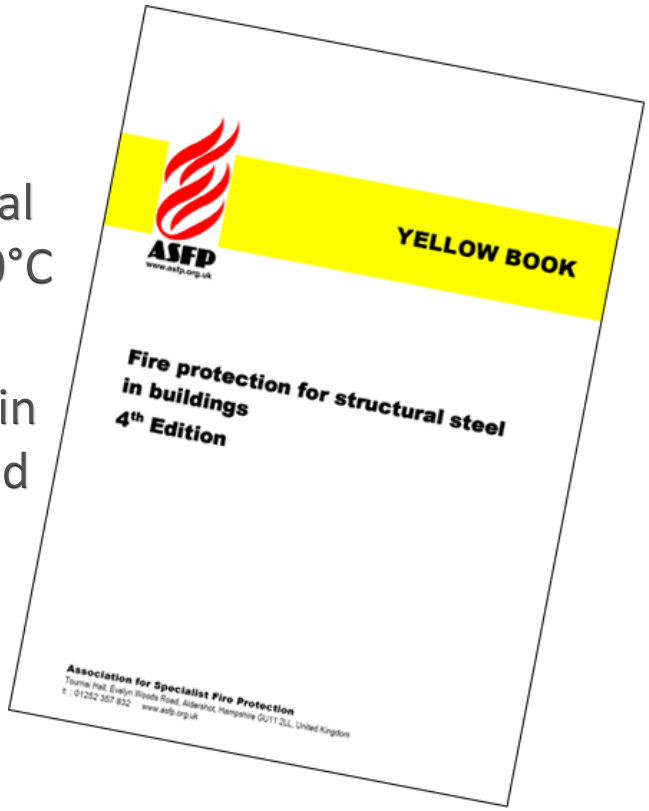
### EC1 or BS 476 Fire Resistance – Fire Limit State



# Fire design methods

**Level 1 Prescriptive fire protection (adopted in Singapore)**

- The "Yellow Book"
  - Simply prescribes enough insulating material to keep steel temperature smaller than 550°C or 620°C
  - No account taken of load level on member in early editions – data still almost ignores load ratio.



# Fire design methods

**Level 2 Performance-based simple member design**

**(adopted in Singapore)**

- BS5950 Part 8 ; EC3 ; EC4
  - Include load level in fire, but try to replicate conditions for a simple member furnace test.
  - Less conservative than Yellow Book, mainly because of Fire Limit State load level.
  - Continuity and load redistribution ignored.

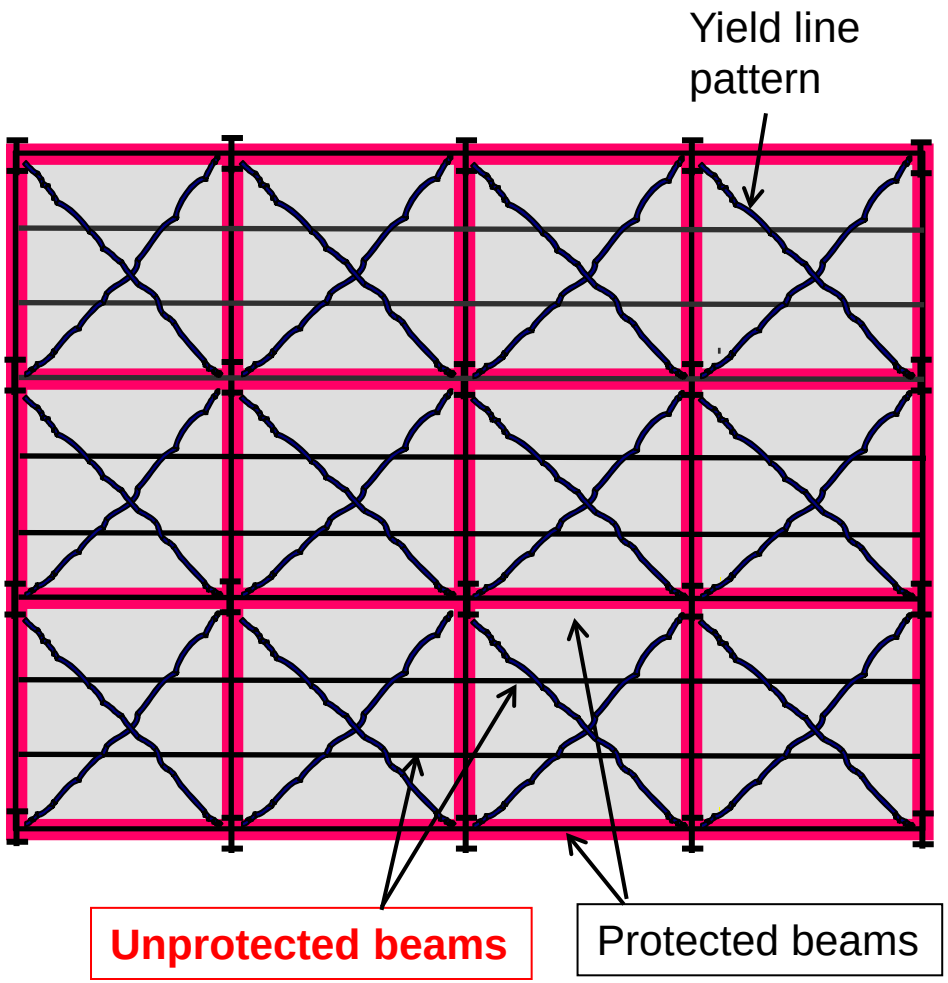
# Fire design methods

## Level 3 Performance-based advanced method

Design guides had been released in UK, SCI Publication P288 and P390, resulting in cost saving of fire protection.

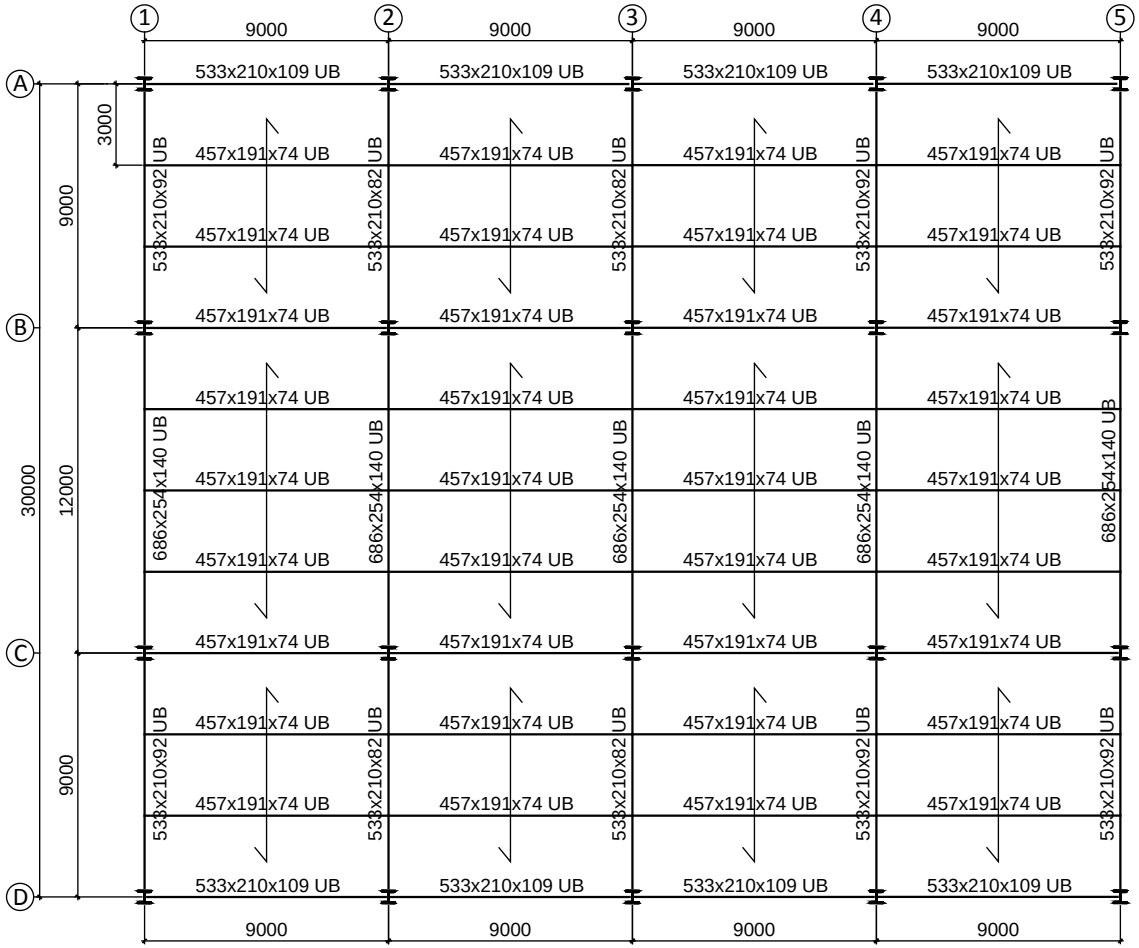
Main and secondary edge beams of each slab panel need to be protected.

Interior secondary beams and the composite slab are unprotected.



# Estimation of cost saving

BS EN 1993-1-1 and BS EN 1994-1-1 are used first.




Composite floor slab using trapezoidal metal decking, normal weight concrete and a single layer of mesh reinforcement.

Variable action: 4kN/m$^2$

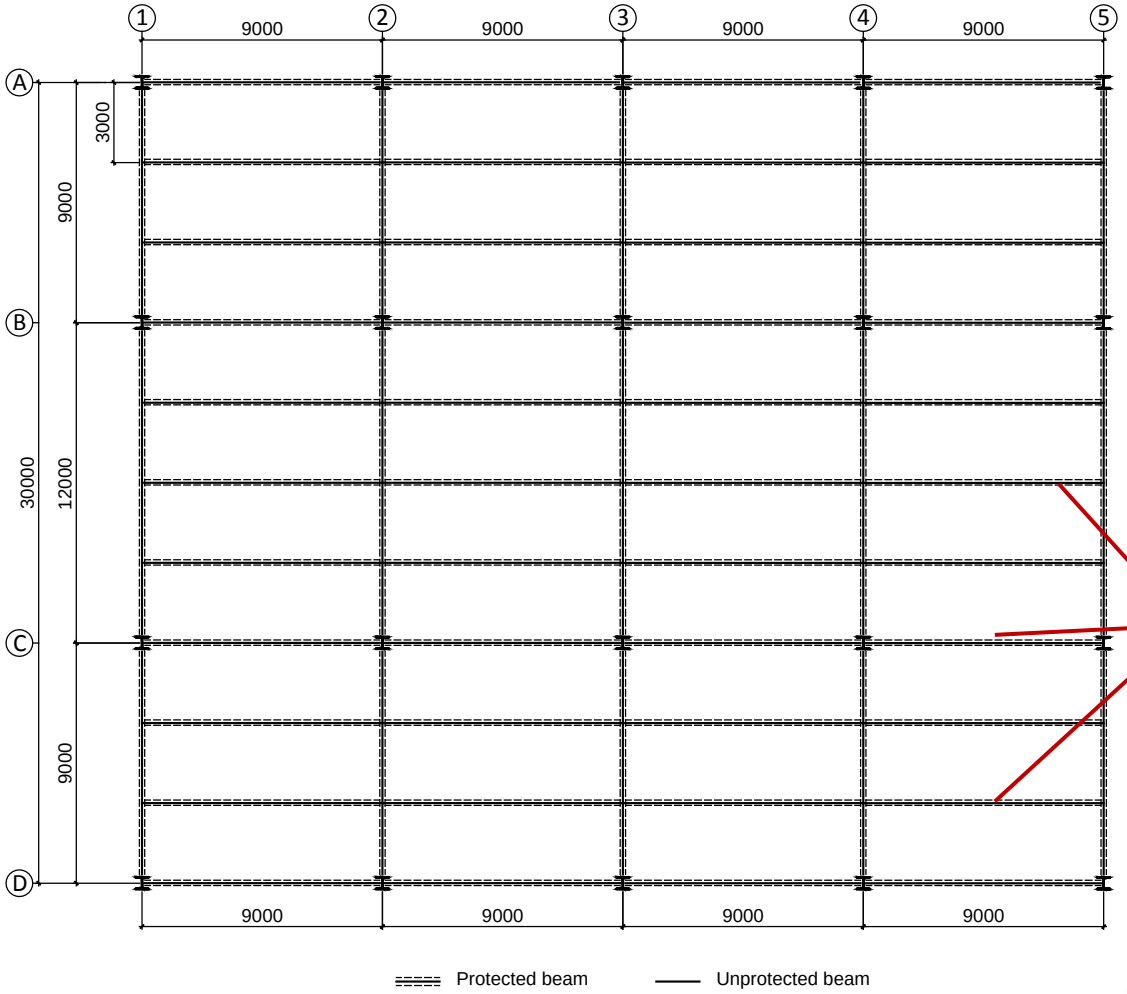
Variable action due to partitions: 1kN/m$^2$

Ceilings and services: 0.7kN/m$^2$

SW of beam: 0.5kN/m$^2$

# Estimation of cost saving

1st fire protection scenario: BS EN 1993-1-2 & 1994-1-2




Using Eurocodes, all the steel beams need to be fire-protected.

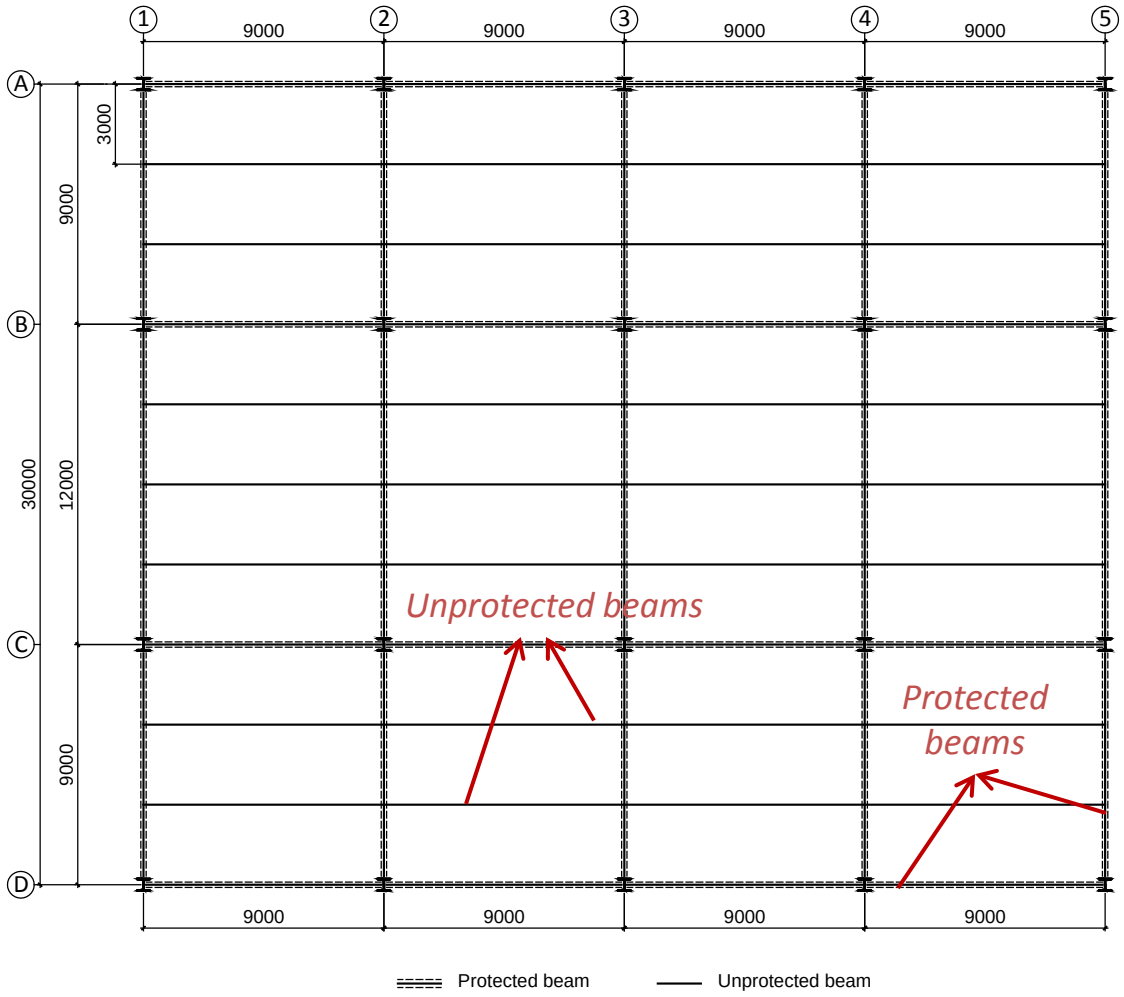
The total length of fire-protected beams is 546 m.

The total length of unprotected beams is 0 m.

*Protected beams*

# Estimation of cost saving

2nd fire protection scenario: P288 & P390




Using P288 & P390, all the steel edge beams of each floor panel need to be fire-protected.

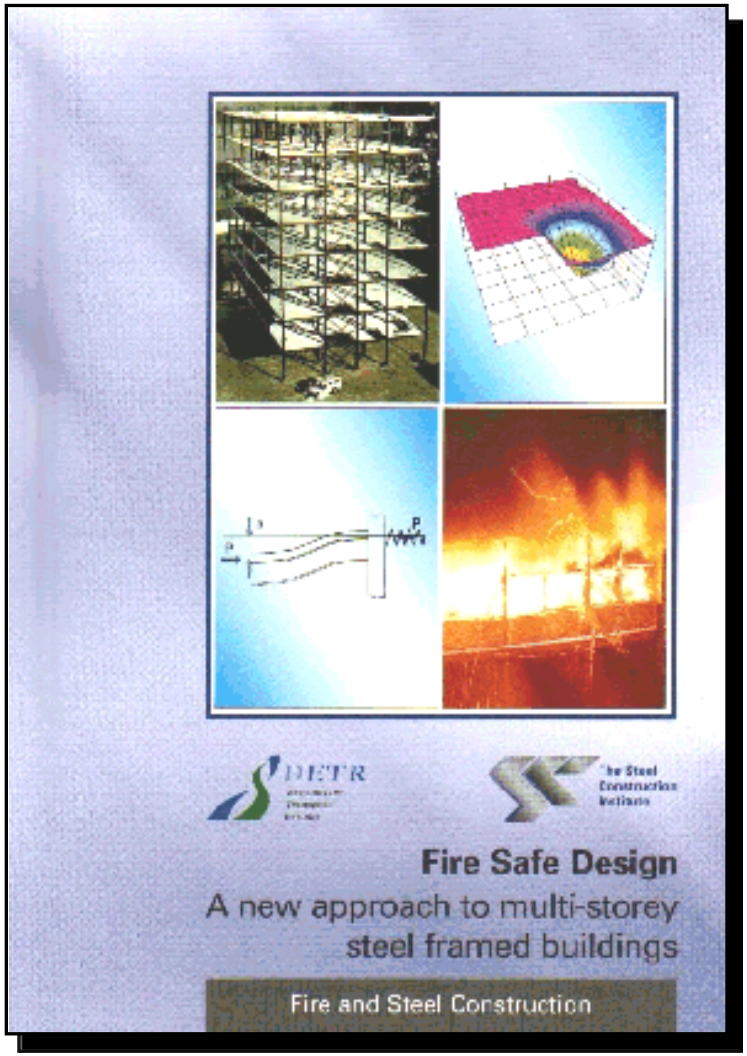
The total length of fire-protected beams is 294 m.

The total length of unprotected beams is 252 m.

-> Cost saving:

$$s = \frac{(546 - 294)}{546} = 46\%$$

# SCI Publication P288

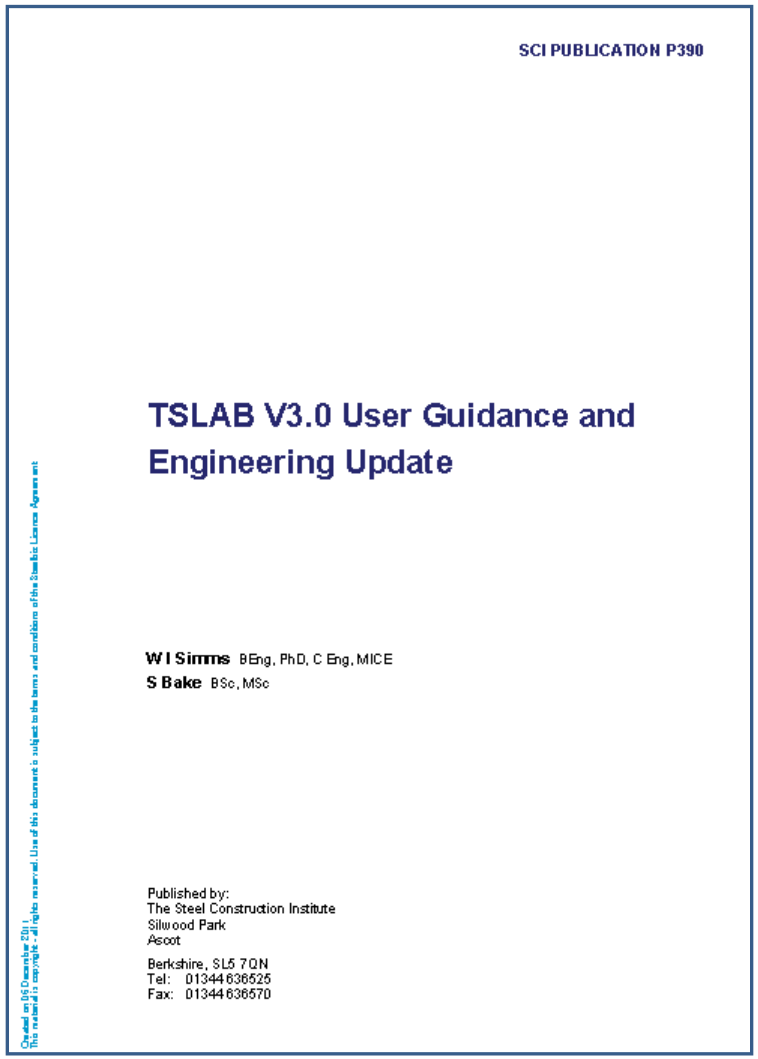



***Post-Cardington Fire Test Guidance***

**Fire safe design**

- Based on observations of Cardington tests and extensive research into the behaviour of composite steel framed buildings in fire
- Checked using new design method from BRE (Colin Bailey)
- Calculation for an isolated composite floor panel with unprotected internal secondary beams.

# SCI Publication P390

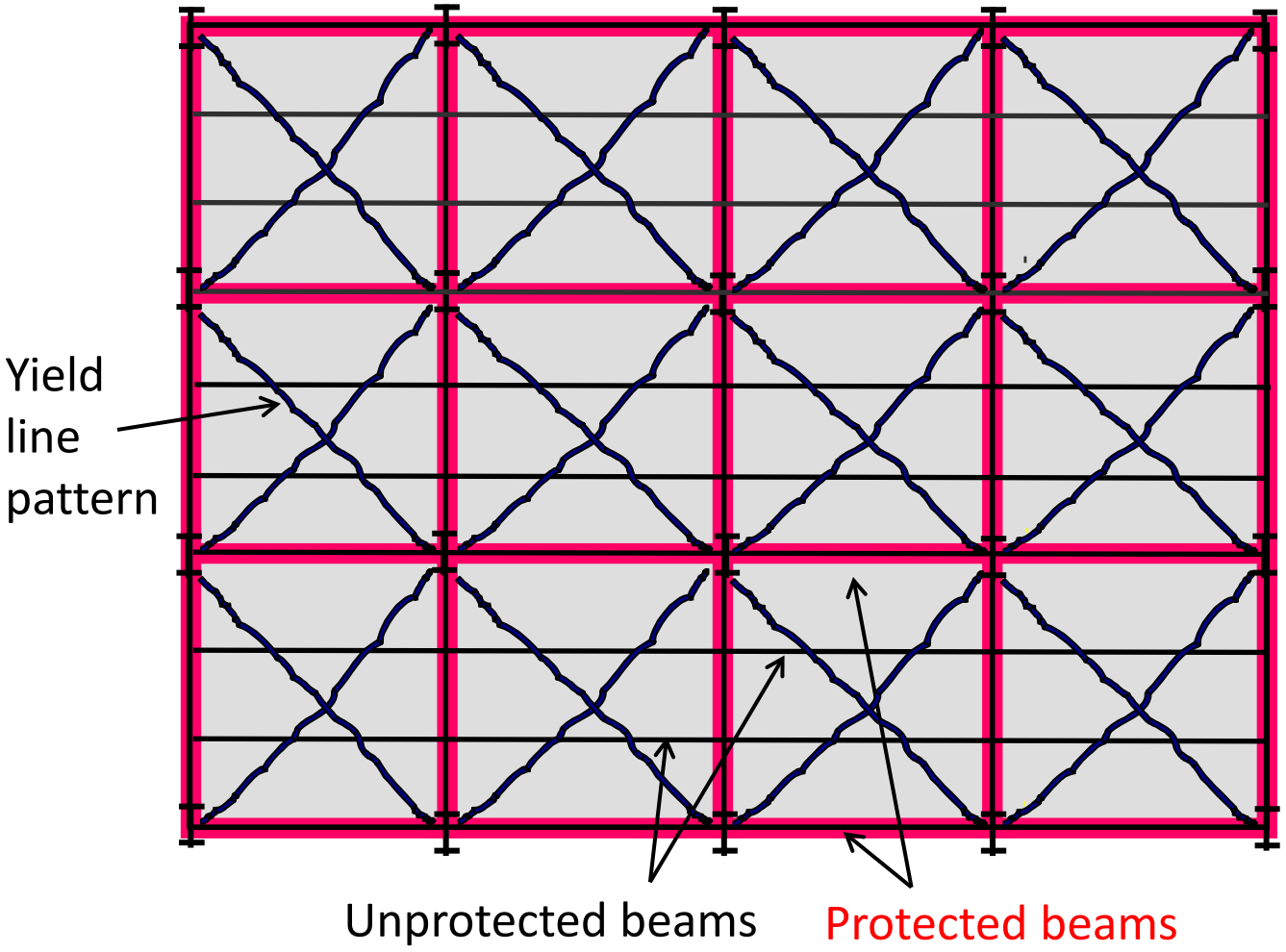



***TSLAB V3.0 User Guidance and Engineering Update***

- Part 1: Provide information on the operation of the TSLAB software v3.0
- Part 2: Engineering update for P288
  - Incorporate Eurocode requirements
  - Include verification for the edge beam capacity
  - Modify the deflection limit

# Principles in SCI P288 & P390

## The Bailey-BRE method



# Principles in SCI P288 & P390

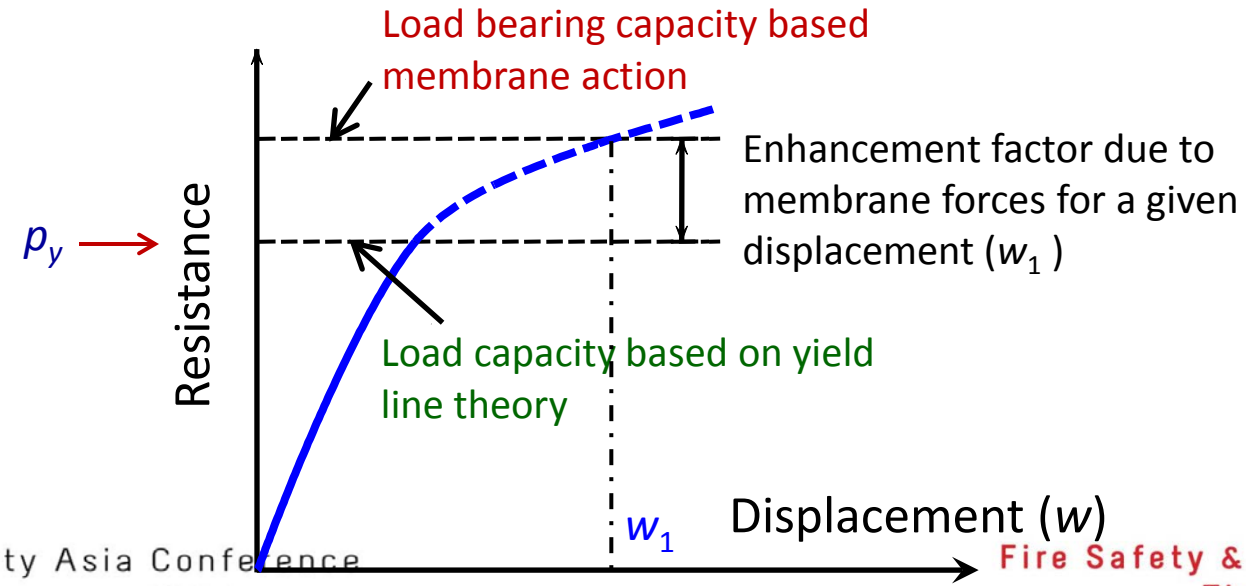
## The Bailey-BRE method

The additional slab capacity provided by TMA is calculated as an enhancement to the small-deflection yield line capacity.

$$p_{ul} = e \times p_y \quad (e > 1)$$

*e* is the enhancement factor due to TMA calculated based on the deflection limit. P288 proposes a deflection limit:

$$w = \frac{\alpha (T_2 - T_1) l^2}{19.2h} + \sqrt{\left(\frac{0.5 f_y}{E_s}\right)_{\text{Reinf't}_{20^0C}} \frac{3L^2}{8}} < w_{max} = \frac{\alpha (T_2 - T_1) l^2}{19.2h} + \frac{l}{30}$$



# SCI P288 & P390

**Conservative**

- Isolated slabs
- Limiting deflection criterion is very arbitrary. May be too restrictive.

**Questions**

- Is this method applicable for composite slab-beam floor systems since previous lab tests focused on isolated concrete slabs?
- Supporting beams are assumed to remain undeflected, but may not be sufficiently protected. Any degradation of the enhancement factor?
- Can TMA be mobilized in different slab configurations?

# Design Commentary

**Objectives**

SCI P288 and P390 and the commentary shall not be used to replace SS EN 1994-1-1:2004 and SS EN 1994-1-2:2005.

They only provide design guidance on an advanced calculation method in design of composite steel-framed buildings to reduce fire-protection costs.

**Restrictions**

The design guide **does not** apply to:

(1) Floors constructed using precast concrete slabs;
(2) Flat slab systems;
(3) Internal floor beams that have been designed to act non-compositely (beams at the edge of the floor slab may be non-composite);
(4) Beams with service openings, *i.e.* composite floor with cellular beams;
(5) Composite slabs that require above 2-hr fire resistance
(6) Not applicable to warehouses or areas with high fire load density

# Calibration of P288 & 390

**Objectives**

- Verify the assumptions of the simple design method
- Verify the use of the simple design method in performance-based fire design of composite slab-beam floor systems.

**Questions**

1. Are the deflection limits (P288 and P390 deflection limits) adequate when compared with the actual deflections achieved in NTU?
2. Can the failure load predictions from P288 and P390 (the Bailey-BRE method) be applied for composite slab-beam systems in fire?

# Calibration of P288 & 390

## NTU fire tests (2010 – 2012)

- Five series with 17 composite beam-slab floor systems in total tested under fire conditions;
- Parameters investigated:

  (1) Presence of unprotected interior secondary beams (Series I)

  (2) Rotational restraint on TMA (Series I)

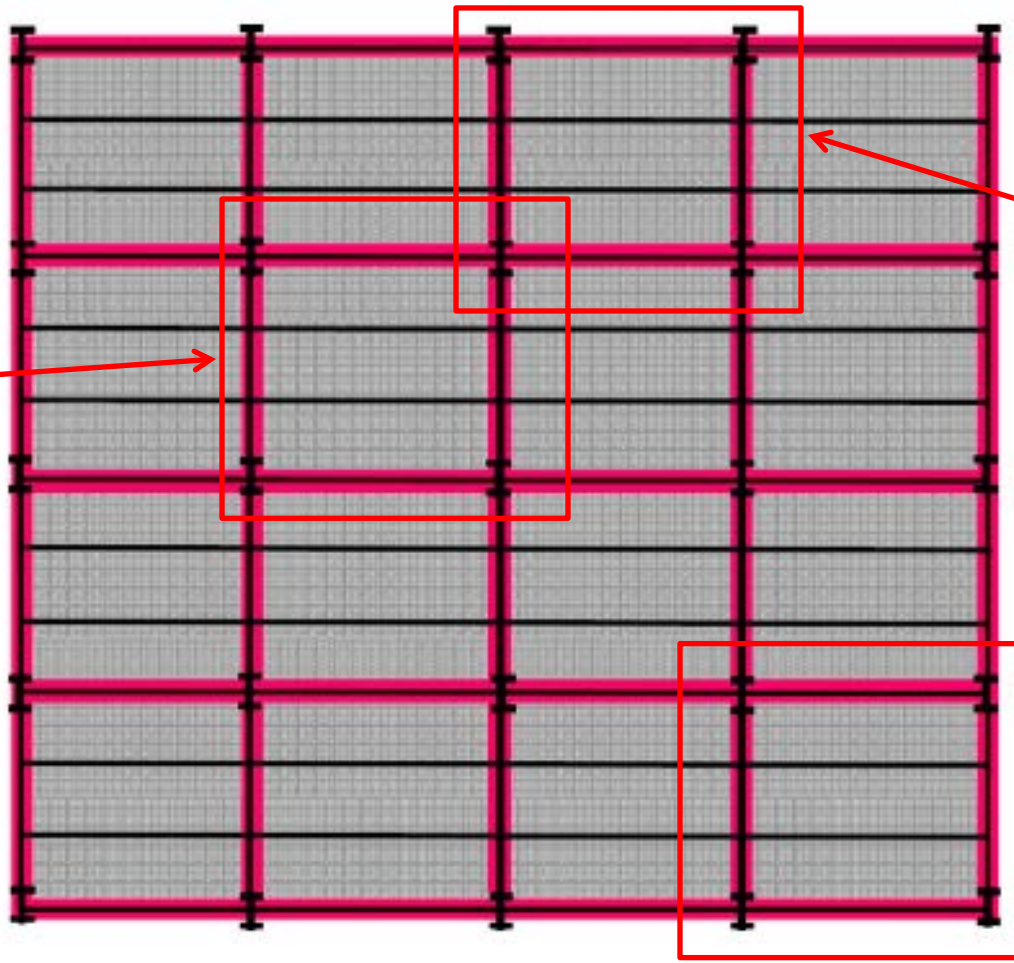
  (3) Stiffness of protected edge beams (Series II)

  (4) Aspect ratio of the slabs (Series IV, V)

  (5) Various boundary conditions: interior (four continuous edges), edge (three continuous edges) and corner (only two continuous edges) panels (Series III, IV, V)

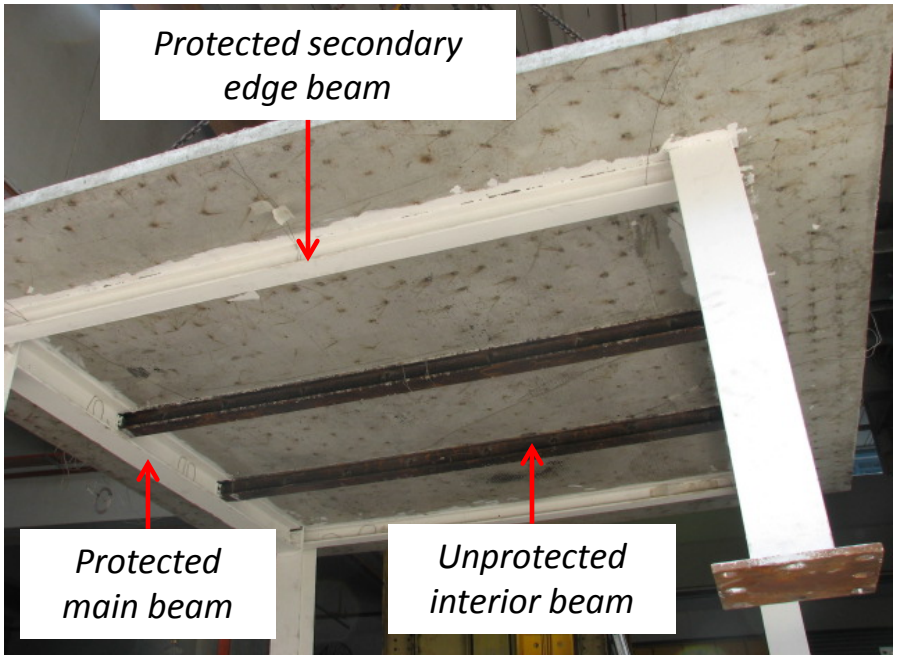
# Calibration of P288 & 390

## Different boundary conditions

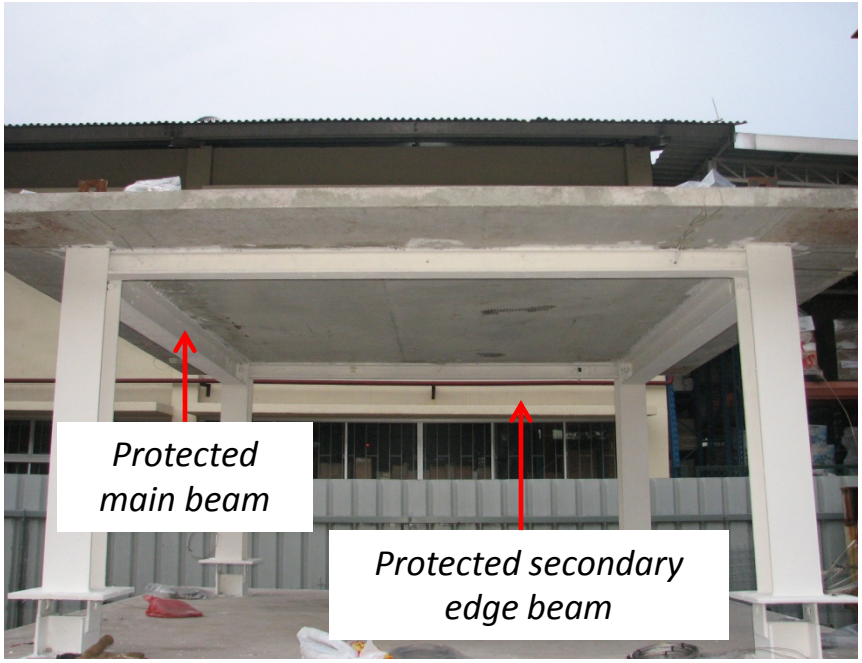



**Typical Building layout**

# Typical Specimens

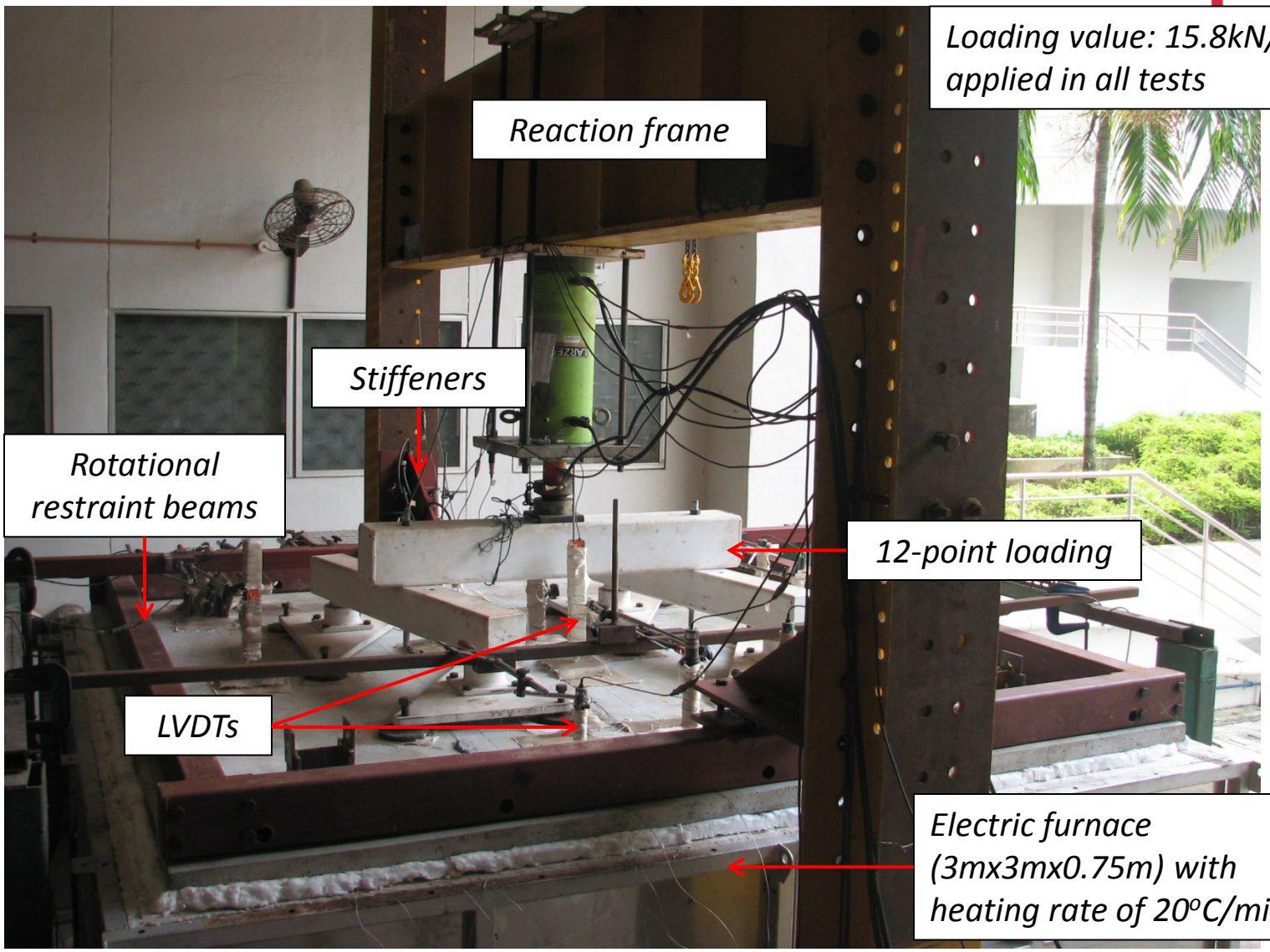



Specimen with interior beams




Specimen without interior beams

# Test Setup (Series I & II)



# Summary of Test Results

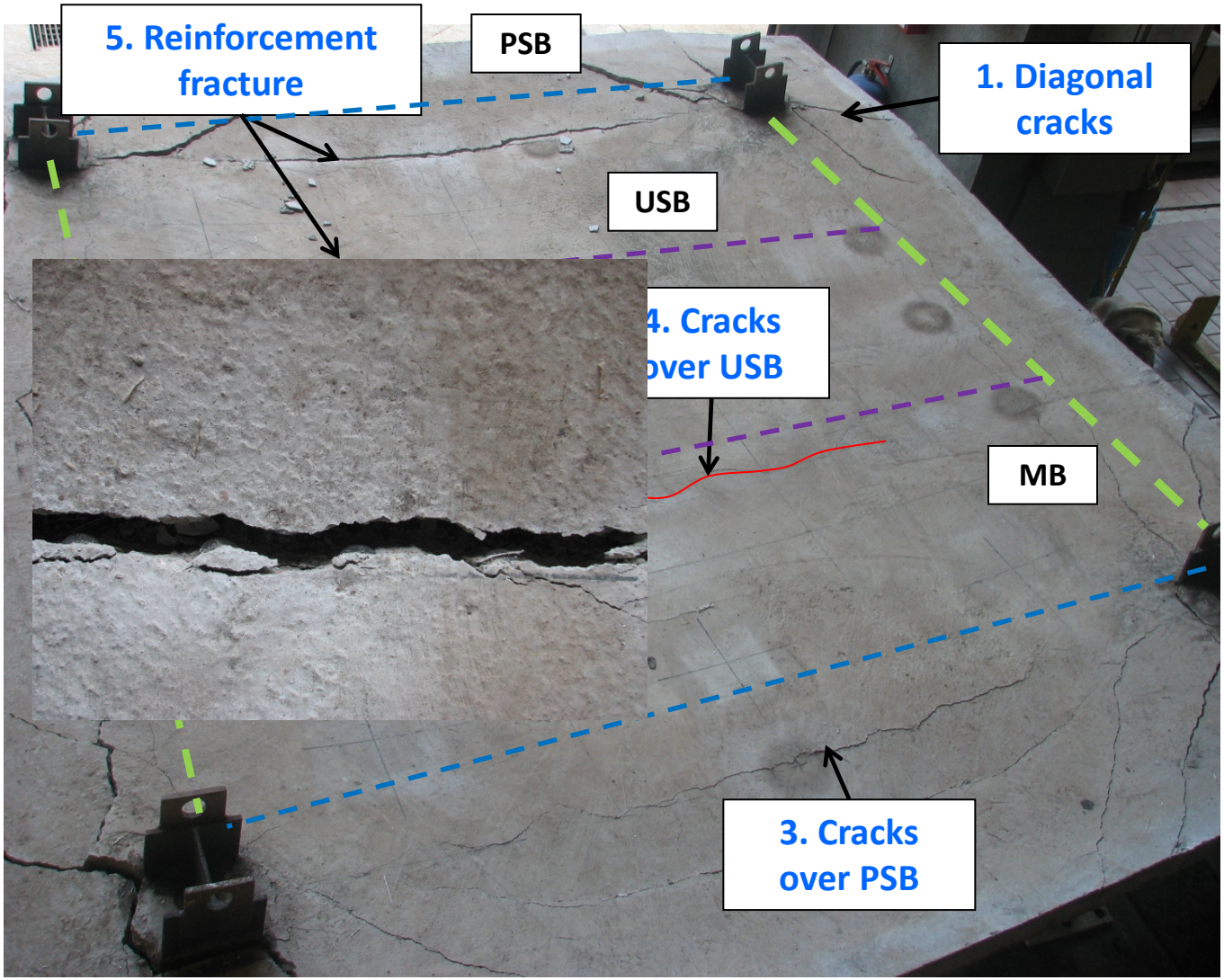
*Slab thickness*

*Maximum deflection / slab thickness*

*Test load / Yield load at failure*

| | $h_s$ | Failure time | Failure Temperature ($^0C$) | | | $p_{test}$ | $p_{y,\theta m}$ | $\delta_{max}$ | $\delta_{max} / h_s$ | $p_{test} / p_{y,\theta m}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | mm | min | $\theta_t$ | $\theta_m$ | $\theta_b$ | kN/m² | kN/m² | mm | | |
| S1 | 55 | 85.8 | 172 | 391 | 630 | 15.6 | 8.0 | 131 | 2.38 | 1.96 |
| S2-FR-IB | 55 | 84.0 | 95 | 512 | 664 | 15.1 | 5.9 | 177 | 3.22 | 2.55 |
| S3-FR | 58 | 45.0 | 60 | 150 | 351 | 16.0 | 10.4 | 115 | 1.98 | 1.54 |
| P215-M1099 | 57 | 72.2 | 108 | 348 | 602 | 15.6 | 8.4 | 124 | 2.17 | 1.86 |
| P368-M1099 | 58 | 74.6 | 118 | 316 | 688 | 15.3 | 8.2 | 118 | 2.03 | 1.87 |
| P486-M1099 | 55 | 98.2 | 127 | 412 | 697 | 15.5 | 8.2 | 139 | 2.53 | 1.89 |
| P215-M1356 | 58 | 76.3 | 101 | 351 | 734 | 15.4 | 8.7 | 121 | 2.09 | 1.77 |
| P215-M2110 | 59 | 198.0 | 228 | 508 | 715 | 15.6 | 8.3 | 143 | 2.42 | 1.88 |

# Typical Failure Mode




**Failure modes**

Full-depth crack & Reinforcement fracture near PSB

MB: main beam;
PSB: protected secondary beam;
USB: unprotected interior beam;

# Question 1: Deflection limits?

**P288 deflection limit:** The P288 deflection limit (Eq. (1)) was calculated using the assumption that ($T_2 - T_1$) is equal to 770°C for fire exposure below 90 minutes and 900°C thereafter.

**P390 deflection limit:** Based on the temperatures measured at failure point, $T_2$ and $T_1$ were determined, and then the P390 deflection limit was calculated.

$$w = \frac{\alpha (T_2 - T_1) l^2}{19.2h} + \sqrt{\left(\frac{0.5 f_y}{E_s}\right)_{\text{Reinf't}_{20^\circ C}} \frac{3L^2}{8}} < w_{max} = \frac{\alpha (T_2 - T_1) l^2}{19.2h} + \frac{l}{30} \qquad (1)$$

$\alpha$ is the coefficient of thermal expansion ($12 \times 10^{-6}$ for normal weight concrete)

$T_2$ and $T_1$ are the bottom and top surface temperatures of the slab respectively;

$h$ is the average depth of the concrete slab;

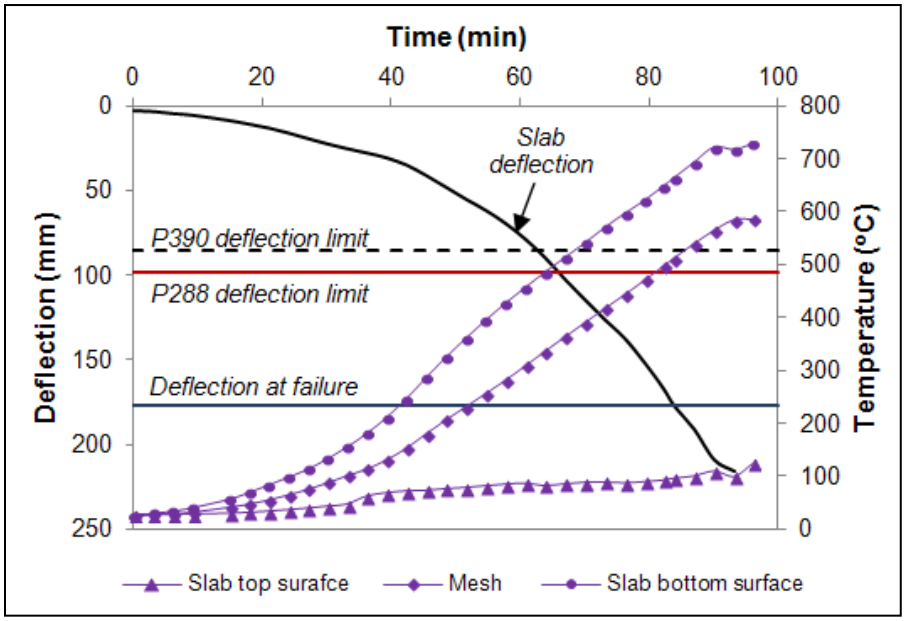
$l$ and $L$ are the shorter and longer spans of the slab panel;

$f_y$ and $E_s$ are the yield and elastic modulus of the reinforcing steel at ambient -temperature.

# Question 1: Deflection limits?

Based on the temperatures measured at failure point, $T_2$ and $T_1$ were determined, and then the deflection limit was calculated.

$$w = \frac{\alpha(T_2 - T_1)l^2}{19.2h} + \sqrt{\left(\frac{0.5 f_y}{E_s}\right)_{\text{Reinf't}_{20^\circ C}} \frac{3L^2}{8}} < w_{\max} = \frac{\alpha(T_2 - T_1)l^2}{19.2h} + \frac{l}{30}$$




**Typical test results**

# Question 1: Deflection limits?

**Table 5** Comparisons of deflection limits (P288 and P390) against test results

| Series | Test | Slab depth | Deflection due to thermal curvature | Deflection due to mechanical strain | P288 deflection limit (Eq. (1)) | P390 deflection limit | Max. deflection in test* | P288 / Test | P390 / Test |
|---|---|---|---|---|---|---|---|---|---|
| | | mm | mm | mm | mm | mm | mm | | |
| I | S1 | 55 | 44 | 54 | 98 | 80 | 131 | 0.75 | 0.61 |
| | S2-FR-IB | 55 | 44 | 54 | 98 | 86 | 177 | 0.55 | 0.49 |
| | S3-FR | 58 | 42 | 57 | 99 | 73 | 115 | 0.86 | 0.63 |
| II | P215-M1099 | 57 | 43 | 57 | 99 | 84 | 124 | 0.80 | 0.68 |
| | P368-M1099 | 58 | 42 | 57 | 99 | 88 | 118 | 0.84 | 0.74 |
| | P486-M1099 | 55 | 52 | 57 | 108 | 90 | 139 | 0.78 | 0.65 |
| | P215-M1356 | 58 | 42 | 57 | 99 | 91 | 121 | 0.81 | 0.75 |
| | P215-M2110 | 59 | 48 | 57 | 105 | 83 | 143 | 0.74 | 0.58 |
| III | ISOCS3 | 60 | 25 | 52 | 86 | 77 | 178 | 0.48 | 0.43 |
| | ISOCS1 | 60 | 28 | 56 | 96 | 84 | 208 | 0.46 | 0.40 |
| | ISOCS2 | 60 | 33 | 51 | 85 | 84 | 189 | 0.45 | 0.44 |
| IV | ICS1 | 60 | 34 | 57 | 97 | 91 | 184 | 0.53 | 0.49 |
| | ECS1 | 60 | 35 | 53 | 93 | 88 | 190 | 0.49 | 0.46 |
| | CCS1 | 60 | 34 | 50 | 90 | 84 | 179 | 0.50 | 0.47 |
| V | ICS2 | 60 | 35 | 52 | 92 | 87 | 153 | 0.60 | 0.57 |
| | ECS2 | 60 | 35 | 50 | 90 | 85 | 158 | 0.57 | 0.54 |
| | CCS2 | 60 | 36 | 51 | 91 | 87 | 160 | 0.57 | 0.54 |
| | | | | | | | **M =** | **0.63** | **0.56** |

** Test terminated when fracture of reinforcement had been identified.*

*The P288 deflection limit is conservative* with the ratio of prediction-to-test deflection varying from 0.45 to 0.86.

*The P390 deflection limit* is even *more conservative* with the ratio of prediction-to-test deflection ranging from 0.40 to 0.75.

# Question 2: Load-bearing capacity?

- The P288 and P390 deflection limits were not used for these comparisons since all the specimens failed at a deflection greater than the P288 and P390 deflection limits.
- Using a greater deflection, a greater enhancement factor will be obtained.
- Total capacity of composite slab-beam systems in fire enhanced by TMA:

$$q_{t,\theta} = e \times p_{y,\theta} + p_{b,\theta}$$

*Load-bearing capacity of the slab enhanced by tensile membrane action*

*In design, the residual flexural strength of the unprotected interior beams in fire is ignored since its contribution is very small.*

*This serves as the 2nd layer of safety.*

# Question 2: Load-bearing capacity?

**Table 6** Comparison of P288 predictions against test results – Series I and II

| *Series* | *Test* | $p_{test}$ *kN/m²* | *MB def. mm* | *PSB def. mm* | *Slab def. mm* | *Relative def. mm* | *Total capacity (kN/m²) (Eq. 2)* | *Prediction / Test (Eq. 2)* |
|---|---|---|---|---|---|---|---|---|
| *I* | *S1* | 15.6 | 28 | 58 | 131 | 88 | 13.1 | 0.84 |
| | *S2-FR-IB* | 15.1 | 56 | 84 | 177 | 107 | 10.4 | 0.69 |
| | *S3-FR* | 16.0 | 33 | 28 | 115 | 85 | 14.6 | 0.92 |
| | | | | | | | ***M* =** | **0.82** |
| *II* | *P215-M1099* | 15.6 | 38 | 57 | 124 | 76 | 14.2 | 0.91 |
| | *P368-M1099* | 15.3 | 51 | 83 | 118 | 51 | 11.9 | 0.78 |
| | *P486-M1099* | 15.5 | 55 | 94 | 139 | 64 | 12.9 | 0.83 |
| | *P215-M1356* | 15.4 | 59 | 88 | 121 | 48 | 12.2 | 0.79 |
| | *P215-M2110* | 15.6 | 39 | 79 | 143 | 84 | 13.1 | 0.84 |
| | | | | | | | ***M* =** | **0.83** |

# Question 2: Load-bearing capacity?

**Table** 7 Comparison of P288 predictions against test results – Series III, IV and V

| *Series* | *Specimen* | $p_{test}$ | $p_{y,\theta}$ | *Slab deflection* $w_m$ | *Average beam defl.* | *Relative slab deflection* | *Enhance ment factor e* | *Total capacity* $ep_{y,\theta}$ | *Predic tion / Test* |
|---|---|---|---|---|---|---|---|---|---|
| | | *kN/m²* | *kN/m²* | *mm* | *mm* | *mm* | | *kN/m²* | |
| *III* | ISOCS3 | 20 | 9.94 | 178 | 83 | 95 | 1.84 | 18.3 | 0.91 |
| | ISOCS1 | 20 | 7.89 | 208 | 80 | 128 | 2.16 | 17.1 | 0.85 |
| | ISOCS2 | 30 | 19.25 | 189 | 130 | 59 | 1.40 | 27.0 | 0.90 |
| | | | | | | | | ***M* =** | **0.89** |
| *IV* | ICS1 | 20 | 7.06 | 184 | 24 | 140 | 2.29 | 16.1 | 0.81 |
| | ECS1 | 20 | 8.72 | 190 | 58 | 122 | 2.10 | 18.3 | 0.91 |
| | CCS1 | 20 | 9.5 | 179 | 81 | 98 | 1.86 | 17.7 | 0.88 |
| | | | | | | | | ***M* =** | **0.87** |
| *IV* | ICS2 | 30 | 17.48 | 153 | 68 | 85 | 1.61 | 28.0 | 0.93 |
| | ECS2 | 30 | 17.97 | 158 | 83 | 75 | 1.54 | 27.6 | 0.92 |
| | CCS2 | 30 | 19.21 | 160 | 91 | 69 | 1.47 | 28.2 | 0.94 |
| | | | | | | | | ***M* =** | **0.93** |

# Conclusions

1. The results showed that all specimens can experience large deflection without global collapse.
2. Tensile membrane action was mobilised in all the tests.
3. The test results also showed that SCI P288 and P390 can be applied safely to composite steel-framed buildings.
4. Currently, NTU is seeking approval from SCDF for the acceptance of SCI P288 and P390.

# Acknowledgement

The research was funded by Agency for Science, Technology and Research (A*Star Singapore) under Grant No. M4070013. The financial support of A*Star is gratefully acknowledged.

This project was conducted jointly with Singapore Civil Defence Force (SCDF). The support of SCDF is gratefully acknowledged.

# Thank you!