Design of Composite Steel Floor Systems for Severe Fires:
The Slab Panel Method

Presentation to the Structures in Fire Forum
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Scope of Presentation

- Basis of design procedure
- Structural performance to be delivered
- Building structure characteristics and detailing requirements
- Background to procedure development
- Future research planned
Basis of Design Procedure

Under ambient temperature conditions:
- The beams support the floor slab
- One way action prevails
- Load path: slab → 2^0 beams → 1^0 beams → columns

Under severe fire conditions:
- Unprotected secondary beams lose strength
- Two way action prevails (slab panel)
- Slab panel supports the beams
- Load path: slab panel → supporting beams → columns
- Slab panel axial forces are in in-plane equilibrium
Under severe fire conditions:

- Slab and secondary beams may undergo appreciable deformation
- Support beams and columns undergo minimal deformation
- Tensile membrane response may be activated
- *Load-carrying capacity* and *integrity* are preserved for full burnout
- Insulation is met for required period
Structural Performance to be Delivered by the Procedure - 2 of 2

Suppression of structural damage controlled by:

- Shielding linings (limited effectiveness)
- Sprinkler protection (extremely effective)

Effective compartmentation is maintained:

- Between floors
- Between firecells, same floor
Building Structure Characteristics Required for Implementation of Slab Panel Design Procedure

(1) Floor slabs
- Concrete: structural grade, NWC or LWC
- Mesh/reinforcement: within slab panel, any grade over supports ≥ 15% uniform elongation
- Solid slabs, trapezoidal and clipped pan deck shapes

(2) Steel beams
- UB, WB, light steel joists, cellular beams

(3) Columns
- UC, WC require passive protection, can use CFSTs

(4) Connections
- Must maintain integrity during heating and cooling down
- Elongation: failure (bolts or welds) to be suppressed
- Same detailing as required for earthquake; NZ standard practice

(4) Overall building stability
- No limitations on lateral load resisting systems
- Building stability not endangered by use of SPM
Detailing Requirements

(1) Floor slab

- Decking fastened to beams; typically composite

- DH 12 trimmer
- DH 12 edge bars; see notes 3-7
- See notes 3-7
- General reinforcement
- Interior support bars:
  - (0.15L_x + 600 mm) for fixed support; note 10
  - Interior support bars:
- DH 12 trimmer
- DH 12 edge bars; see notes 3-7
- DH 12 support for edge bar if required
- DH 12 lapped trimmer bar
- DH 12 edge bar with standard hook
- Specified cover
- Mesh
- DH 12 support for edge bar if required
- DH 12 lapped trimmer bar
- 50 mm
- Min 6x stud diameter from stud centre line
- Edge and trimmer bar reinforcement in slab panel 2 is not shown
- Passive Protection Surrounds Base of Cleat in Contact with the Primary Beam
- Slab panel 1
- Slab panel 2
- 600 mm for simple support; note 9
- Interior primary support beam
- General reinforcement
- Deck trough bar (optional)
First design the floor and structural system for gravity and lateral loading conditions, then:

**Step 1:** Determine the size of the slab panel and location of the slab panel supports

**Step 2:** Determine which of the internal supports can carry negative moment

**Step 3:** Start with recommended reinforcement contents

**Step 4:** Input all variables and check capacity; increase as recommended in report
This uses the modified Bailey model, ie:
\[ w^* = G + Q_C \] from Loadings Standard
\[ w_u = (w_{yl\theta} - w_{yl\theta, ss}) + w_{yl\theta, ss}e \]
\[ w_u \geq w^* \text{ required} \]

where:
- \( w^* \) = fire emergency distributed load
- \( w_u \) = slab panel load carrying capacity
- \( w_{yl\theta} \) = yieldline load carrying capacity in fire
- \( w_{yl\theta, ss} \) = simply supported yieldline load carrying capacity in fire
- \( e \) = tensile membrane enhancement factor
  \[ = fn (L_x, L_y, m_x, m_y, t_{eq}, t_o, h_{rc} f_{yr, \theta}, E_{yr, \theta}) \]
- \( t_o, h_{rc} \) are slab thickness, deck rib height
- \( f_{yr, \theta}, E_{yr, \theta} \) are for reinforcement including secondary beams
This is additional to the Bailey model:

\[ w^* = G + Q_u \]
\[ v^* = w^*(L_x / 2) \]
\[ v_{u,\text{slab}} = \phi_{\text{fire}} v_c d_v \]

\[ \phi_{\text{fire}} = 0.89 \text{ from standard} \]
\[ v_c = \text{conc. slab shear capacity} \]
\[ d_v = \text{effective shear depth} \]
\[ V_{u,\theta,\text{sb}} = \text{shear capacity of secondary beam in fire} \]
\[ S_{\text{sb}} = \text{spacing of secondary beams} \]

\[ v^* \leq v_{u,\text{slab}} + \frac{V_{u,\theta,\text{sb}}}{S_{\text{sb}}} \text{ required} \]
Development Work Undertaken

- 18 stage experimental and analytical development programme undertaken
- Steps presented in following slides
- Covers from 1995 to 2011

- Demonstrated performance of large scale composite floor systems
- Showed systems with unprotected beams and protected columns have high fire resistance
Step 2: BRE Design Model and Test 2000

- Colin Bailey Tensile Membrane Model, UK BRE
- Large scale ambient temperature tests on lightly reinforced slabs to validate behaviour
Step 3: First Edition of SPM 2001

- Generalised application of Bailey model for review
- HERA DCB No 60, February 2001
- Incorporating moment capacity of secondary beams
- General formula for yieldline determination
  - includes support moment contribution
- Limits on application set by Bailey for:
  - integrity
  - maximum deflection
Step 4: FEM of Cardington Test Building 2002 published 2004

- Modelling of Cardington BRE large scale fire test
- Set of interlinked composite beams
- Interlinking required to obtain good agreement with experimental deflected shape
- Showed the two way nature of the floor system behaviour must be considered to replicate experimental behaviour

![Diagram of Cardington BRE large scale fire test]

BRE large compartment test

- part of PhD research project
- details as shown opposite and below
- all slabs withstood 180 minutes ISO fire without failure: see next slide
Results of tests

<table>
<thead>
<tr>
<th>Slab</th>
<th>Applied load, $W_a$ (kPa)</th>
<th>Ambient temperature</th>
<th>At 3 hours in the ISO fire</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$W_{u,a}$ (kPa)</td>
<td>Load ratio, $\frac{W_{u,a}}{W_a}$</td>
<td>Max. Steel Temp. ($^\circ$C)</td>
</tr>
<tr>
<td>1 661 Flat slab</td>
<td>5.40</td>
<td>20.0</td>
<td>0.270</td>
</tr>
<tr>
<td>2 HD12 Flat slab</td>
<td>5.40</td>
<td>28.2</td>
<td>0.191</td>
</tr>
<tr>
<td>3 D147 Flat slab</td>
<td>5.40</td>
<td>13.3</td>
<td>0.406</td>
</tr>
<tr>
<td>4 Hibond slab</td>
<td>5.52</td>
<td>70.2</td>
<td>0.079</td>
</tr>
<tr>
<td>5 Traydec slab</td>
<td>6.12</td>
<td>75.0</td>
<td>0.082</td>
</tr>
<tr>
<td>6 Speedfloor</td>
<td>5.16</td>
<td>55.1</td>
<td>0.094</td>
</tr>
</tbody>
</table>

Load ratio $\leq 1.0 \Rightarrow$ no tensile membrane enhancement required

Load ratio $> 1.0 \Rightarrow$ tensile membrane enhancement is required

- Incorporating results of furnace tests
- HERA DCB No 71, February 2003
- Improved determination of slab and reinforcement temperatures
- Revised reinforcement limits for integrity
- Relaxation of maximum deflection and limits on e
Step 7: Development and Validation of FE Model 2003

- 6 test slab panels modelled
- Best fit to mid-span deflection made for each case
- Accuracy of models also compared with:
  - reinforcement strains
  - edge deflections and rotations

Example shown for *Speedfloor* slab
FEM used to extend experimental testing to determine the influence of:

- effect of deformation in slab panel edge supports (no effect on capacity; increases panel midspan deformation, 65% contribution)
- horizontal axial restraint is significant, even at low levels (100kN/m stiffness)
- slabs of 4.15m x 3.15m, 8.3m x 6.3m and 8.3m x 3.15m analysed: 8.3m x 6.3m result shown below
Step 9: Confirming the SPM Assumption on Secondary Beam Contribution to Slab Panel Behaviour 2004/2005

FEM used to extend experimental testing to determine the influence of:

- contribution of the unprotected secondary beams: contribute to slab panel moment resistance as shown below

All steel tension forces are calculated for their design elevated temperatures
Step 10: Comparison of SPM Prediction with FEM for Real Floor System 2004/2005

- First analysis of a complete floor system
- 550m² 19 storey building built 1990
- Trapezoidal decking on secondary beams with central primary beam
- Floor divided into two slab panels
- This is the design example used in all editions of the procedure
Step 11: Distribution of Slab Panel Loads into Supporting Members for Strength Determination 2005

- Based on yieldline pattern
- Important is realistic to avoid support beam failure and slab panel plastic collapse (Abu)
- FEM modelling showed more realistic than ambient temperature design practice

<table>
<thead>
<tr>
<th></th>
<th>G+Q</th>
<th>Fire - 44min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hand calc.(HC)</td>
<td>ABAQUS (ABQ)</td>
</tr>
<tr>
<td>Column-1 (A-5)</td>
<td>64.8</td>
<td>43.5</td>
</tr>
<tr>
<td>Column-2 (B-5)</td>
<td>159.9</td>
<td>180.2</td>
</tr>
<tr>
<td>50% of Column A-4</td>
<td>18.9</td>
<td>29.6</td>
</tr>
<tr>
<td>Total</td>
<td>243.6</td>
<td>253.3</td>
</tr>
</tbody>
</table>

Slab panel central vertical downwards deflection versus time shows three stages of behaviour:

Stage 1: Decreasing rate of deflection with time due to thermal effects

Stage 2: Constant rate of deflection with time due to loss of yieldline capacity balanced by enhanced tensile membrane resistance

Stage 3: Increasing rate of deflection to fracture

- $\Delta_{\text{limit}} = \min (\Delta_1, \Delta_2) C_{\text{ISO}}$
- $C_{\text{ISO}} = 0.00743 \ t_{\text{eq}} + 0.7768$
- $\Delta_1, \Delta_2$ based on Bailey limits
• Peer reviewed internationally
• Now used in most multi-storey composite steel floor fire engineered buildings in New Zealand
Example of SPM application to office building: 2007
Step 14: Incorporating Orthotropic Reinforcement Conditions into Tensile Membrane Model 2008/2009

- Undertaken by AP Tony Gillies, Lakehead University, Canada and graduate students
- Incorporates tensile membrane model updates from Bailey
- All applications are orthotropic due to temperature gradient effects even in regular slabs
Step 15: Improving the Accuracy of the Tensile Membrane Model 2009

- Correct orientation of tensile membrane fracture plane
  - tensile membrane fracture may be in Lx or Ly direction
  - whichever is the weaker

- Maintaining equilibrium at yieldline intersections
  - Steel across yield-lines cannot be above yield
Step 15a: Consideration of “double dipping” in regard to tension action in slab panel

- Can tension action in reinforcement and beams be used in yieldline moment and tensile membrane enhancement?
  - Yes, until a full height fracture crack opens up along a yieldline

If $R_{tsy} < R_{tsx}$ (long direction weaker):
  - Final fracture not along yieldline
  - No loss of yieldline moment capacity due to tensile membrane action

If $R_{tsx} < R_{tsy}$ (short direction weaker):
  - Final fracture along yieldline CD
  - Loss of yieldline moment capacity near final collapse
  - Beyond time to failure predicted from method
Step 16: Including Limitation Based on Compression Failure of Concrete Compression Ring 2010

- Avoidance of concrete compression failure in edge of slab
- Calculation of design width of concrete in compression
- Ensuring this is not also included in composite slab contribution to supporting beam

\[
\begin{align*}
R_{tc} &= A_t f_y \\
R_{cc} &= 0.85 f'_c \quad \text{C.G. of concrete resistance} \\
0.85 f'_c &\quad \text{C.G. of steel resistance} \\
\end{align*}
\]
Current 4th year student project due for completion September 2011

Objectives:
1. Review temperatures used for unprotected steel beams in SPM 2006 against 6 recent large scale fire tests
2. Review relationship between fire gas temperature and steel beam temperature against same 6 tests
3. Review calculated deflections against test deflections
4. Make recommendations for changes to SPM 2006 criteria

Tests used:
1. Cardington Demonstration Furniture Test 1995
2. Cardington Corner Test 1995
3. Cardington Corner Test 2003
4. Mokrsko
5. FRACOF
6. COSSFIRE
### Step 17: Critical Review of Design
Temperatures of Unprotected Secondary Beams within Slab Panel and SPM Deflection Limits 2011

<table>
<thead>
<tr>
<th>Fire test</th>
<th>$\phi_{\text{fire}}$</th>
<th>$w^*_\text{test}$</th>
<th>$w^*<em>\text{test}/\phi</em>{\text{fire}}$</th>
<th>$\Delta_{\text{limit}}$</th>
<th>$\Delta_{\text{test}}$</th>
<th>$\Delta_{\text{test}}/\Delta_{\text{limit}}$</th>
<th>$t_{\text{eq}}$</th>
<th>Notes on $t_{\text{eq}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardington Furniture Test</td>
<td>7.09</td>
<td>4.94</td>
<td>0.7</td>
<td>726</td>
<td>642</td>
<td>0.88</td>
<td>54</td>
<td>Calculated from $t_{\text{eq}} = e_k b W_f$</td>
</tr>
<tr>
<td>Cardington Corner Test</td>
<td>6.47</td>
<td>4.94</td>
<td>0.76</td>
<td>754</td>
<td>388</td>
<td>0.51</td>
<td>62</td>
<td>Calculated from $t_{\text{eq}} = e_k b W_f$</td>
</tr>
<tr>
<td>Cardington 2003 Test</td>
<td>5.25</td>
<td>7.15</td>
<td>1.36</td>
<td>777</td>
<td>919</td>
<td>1.18</td>
<td>57</td>
<td>Calculated from $t_{\text{eq}} = e_k b W_f$</td>
</tr>
<tr>
<td>Mokrsko Test</td>
<td>7</td>
<td>6.6</td>
<td>0.94</td>
<td>864</td>
<td>892</td>
<td>1.03</td>
<td>65</td>
<td>Calculated from $t_{\text{eq}} = e_k b W_f$</td>
</tr>
<tr>
<td>FRACOF Test</td>
<td>19.55</td>
<td>6.89</td>
<td>0.35</td>
<td>750</td>
<td>460</td>
<td>0.61</td>
<td>120</td>
<td>Duration heating curve in furnace</td>
</tr>
<tr>
<td>COSSFIRE Test Option 1 (Note 1)</td>
<td>8.91</td>
<td>6.41</td>
<td>0.72</td>
<td>668</td>
<td>465</td>
<td>0.7</td>
<td>120</td>
<td>Duration heating curve in furnace</td>
</tr>
<tr>
<td>COSSFIRE Test Option 2 (Note 1)</td>
<td>4.19</td>
<td>6.41</td>
<td>1.53</td>
<td>668</td>
<td>465</td>
<td>0.7</td>
<td>120</td>
<td>Duration heating curve in furnace</td>
</tr>
<tr>
<td><strong>Average value of 6 tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>0.81</strong></td>
<td><strong>0.82</strong></td>
<td></td>
</tr>
</tbody>
</table>

Note 1: The COSSFIRE test panel underwent a support failure of one short edge supporting beam. The first option is the SPM calculation on the basis of all support beams effective. The second option is the SPM calculation on the basis that one $L_x$ support beam is ineffective and therefore the slab panel length $L_y$ is doubled as that support becomes an effective centreline of a larger panel.
Step 18: Rewriting of SPM Software 2011

- Much more user-friendly input/output
- Written in current version Visual Basic
- Data input screens include diagrams and explanatory text
- Currently in beta version
- Detailed QA over 2011/2012 summer
- Incorporates all 17 stages of development
Potential Future SPM Related Research
Strength and Stiffness of Slab Panel Edge Support Beams

- Following on from 2011 research into SPM
- Student to be found
- Supervisors AP Charles Clifton and Dr Tony Abu
- Status:
  - Slab panel support beams must have sufficient strength and stiffness to avoid a plastic collapse mechanism
  - What are the limits?
• These are becoming more common
• Student to be found
• Main Supervisor Charles Clifton? or Tony Abu?
• Status:
  – web contribution currently ignored
  – Is this accurate
Slab Panel Performance with Steel Fibre Reinforcement

- General determination following on from 2011 research
- Main Supervisor ??
- Student to be found
- Status:
  - Linus Lim in 2000 undertook PhD 6 slab panel tests and procedure verification
  - Repeat tests with fibres instead of general mesh
  - These used in conjunction with additional support reinforcement?
• Main Supervisor ??
• Student to be found
• Determine by large scale experimental testing or modelling the adequacy of the current SPM detailing provisions
• Three large scale fire tests have recently supported the need for these with premature failures when details not included:
  • Mokrsko: slab pulled off slab panel edge support beam due to lack of edge and anchor bars around shear studs
  • Fracof: fracture of mesh where not adequately lapped within slab panel
  • VUT: shear failure at interior support where interior support bars too short and wrongly placed


KIRBY, B. 1998. The Behaviour of a Multi-Storey Steel Framed Building Subject to Fire Attack-Experimental Data: Also data from BRE, Cardington, on the Corner Fire Test and the Large Compartment Fire Test, 1996. Swinden: British Steel Swinden Technology Centre.


MAGO, N. 2004a. Influence of slab panel edge sagging in fire - Stage 2 of the SPM: Concise summary, HERA Report R4-118.1. Manukau City, NZ: New Zealand HERA.

MAGO, N. 2004b. FEA of three WRCSI fire tests: concise summary, HERA Report R4-118.2. Manukau City, NZ: New Zealand HERA.

MAGO, N. 2004c. Composite floor system performance in ISO 100 min and natural fire teq 44 min: concise summary, HERA Report R4-118.3. Manukau City, NZ: New Zealand HERA.

MAGO, N. 2005. DCB No 71 with secondary beams or Speedfloor joists: concise summary, HERA Report R4-118.4. Manukau City, NZ: New Zealand HERA.


THE END