In this presentation, I will cover in more detail the strength design of the test slabs in accordance with AS 3600–2009.

In Part 2B we will compare the design strengths with the test results.
The Part 2 presentations are based on this supplementary joint report to the Curtin Test Report, which was prepared for the Peer Review Panel.

It describes in detail the strength design of all of the slabs from the SSOW, DSOW and TW test series, including an additional trial SSOW test slab that was tested before the SSOW slabs were poured. The Edge-Restraint Test slab is not considered. Therefore, there are fourteen slabs considered in total.

All cross-sections were conservatively treated as singly reinforced for this assessment.
Reiterating, "unrestrained" slabs had their ends effectively pinned, and "restrained" slabs had their ends or edges effectively fully built-in, and the slabs were designed assuming these ideal support conditions.
It is clear from the overview shown here that strength design is the primary consideration of the presentation.

The slabs were principally designed for ultimate strength, rather than serviceability limit states like vertical deflection or cracking. However, each slab was practically proportioned with a span-to-depth ratio representative of normal construction, and also reinforced in all flexural tensile regions. Also, on account of the realistic span-to-depth ratios and the test loading configurations, failure due to flexure rather than vertical shear was anticipated.
In accordance with AS 3600–2009, at all potentially critical sections with Class L main bars, these two inequalities must be satisfied, under normal assumed design conditions of one-way or two-way reinforced-concrete slabs ignoring in-plane forces.

When calculating the design moment capacity, $\phi M_{uo}$, the normal upper limit of 0.8 for $\phi$ has been reduced to 0.64, i.e. a 20% penalty has been applied compared with using Class N bars.

For vertical shear design in the absence of any vertical shear reinforcement, no penalty is applied when using the well-known empirical Zsutty equation to calculate $V_{uc}$. 

**Strength Design to AS 3600–2009**

At all potentially critical sections with Class L main bars:

- For bending without compression:
  \[ \phi M_{uo} \geq M^* \]
  where \[ 0.6 \leq \phi (=1.19 - 13k_{uo}/12) \leq 0.64 \]

- For vertical shear:
  \[ \phi V_{uc} \geq V^* \]
  where $\phi = 0.7$
This table from the paper summarises all the values of design moment capacity in pure bending, $\phi M_{\text{uo}}$, calculated ignoring compressive membrane action, and design shear capacity, $\phi V_{\text{uc}}$, of the potentially critical cross-sections in the positive (sagging) and negative (hogging) moment regions of all the test specimens, conservatively assuming they are singly reinforced. Nominal slab dimensions, concrete covers, steel areas and design material properties were used.

<table>
<thead>
<tr>
<th>Test Series</th>
<th>Test Specimen No.</th>
<th>$\phi M_{\text{uo}}$ (N.m/m)</th>
<th>$\phi V_{\text{uc}}$ (kN/m)</th>
<th>$\phi M_{\text{uo}}$ (N.m/m)</th>
<th>$\phi V_{\text{uc}}$ (kN/m)</th>
<th>$\phi M_{\text{uo}}$ (N.m/m)</th>
<th>$\phi V_{\text{uc}}$ (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSOW</td>
<td>SSOW-ST1</td>
<td>9.29 (50.74)</td>
<td>7.71 (47.63)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>SSOW-ST2</td>
<td>7.71 (47.63)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>SSOW-ST3</td>
<td>7.71 (47.63)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>SSOW-ST4</td>
<td>9.29 (50.74)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>SSOW-ST5</td>
<td>14.93 (60.36)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>SSOW-ST6</td>
<td>15.30 (63.48)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>SSOW-ST7</td>
<td>13.50 (58.42)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>SSOW-ST8</td>
<td>14.04 (61.66)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>SSOW-TRIAL</td>
<td>9.29 (50.74)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>DSOW</td>
<td>DSOW-ST1</td>
<td>7.71 (47.63)</td>
<td>9.29 (50.74)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>DSOW-ST2</td>
<td>7.71 (47.63)</td>
<td>9.29 (50.74)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>DSOW-ST3</td>
<td>7.71 (47.63)</td>
<td>9.29 (50.74)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>DSOW-ST4</td>
<td>7.71 (47.63)</td>
<td>9.29 (50.74)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TW</td>
<td>TW-ST1</td>
<td>9.29 (50.74)</td>
<td>7.71 (47.63)</td>
<td>8.21 (49.99)</td>
<td>6.91 (46.15)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
The design action effects were determined for the normal combination of factored actions $1.2G + 1.5Q$ with dead load $G$ and live load $Q$ using at least one of the methods of analysis permitted by AS 3600 listed here.

Static analysis was applied to all of the unrestrained, simply-supported SSOW slabs.

Linear elastic analysis was applied to restrained slab SSOW-ST1, all four redundant, continuous two-span DSOW slabs, and also redundant one-way strips in the two-way slab.

Finite-element analysis was used to design the two-way slab when it was loaded at four points to failure, assuming the concrete was uncracked and behaved linear elastically.

Non-linear frame analysis accounting for non-linear geometric effects was used to design the restrained SSOW and DSOW slabs (SSOW-ST1, DSOW-ST1 and DSOW-ST2) taking into account compressive membrane action assuming the negative and positive plastic hinges formed simultaneously according to plastic theory derived by Park and Gamble in their textbook on reinforced-concrete slabs.

Simplified flexural analysis in accordance with Clause 6.10.3 Simplified method for reinforced two-way slabs supported on four sides was applied to the two-way slab for the initial water proof-loading stage.
The results of the static analysis of the simply-supported slabs are summarised in this table in the paper.

For example, the ultimate design load for the slabs loaded with 4 line loads is $4P^*$ (which equals $1.5Q$). $V^*_{\text{max}}$ is the corresponding maximum design end shear force.
Statically indeterminate slab SSOW-ST1 was designed three ways, with all the results shown in Table 3 of the paper, namely: linear elastic analysis in accordance with Clause 6.2 of AS 3600–2009; plastic analysis ignoring compressive membrane action; and plastic analysis including compressive membrane action. It can be seen that the design loads and end shear force increased substantially for each of the plastic analysis methods, to the extent that vertical shear capacity actually governed the design taking into account membrane action as a non-linear frame analysis method.

This is despite Clause 6.7 of AS 3600 requiring Class N bars to be used throughout for flexural reinforcement when plastic collapse analysis is used.
The 5 mm uplift at the centre support theoretically represented a severe loading event for the two DSOW slabs concerned.

Ignoring the effects of flexural cracking, linear elastic analysis showed that the bending moments induced could well exceed the negative and positive design moment capacities. A designer could conclude that support settlement itself would fail these slabs, and that they had no reserve load-carrying capacity. However, this was ignored in design, in accordance with AS 3600.
Statically indeterminate slabs DSOW-ST1 & ST2 with restrained ends were also designed the three ways listed here, with all the results shown in Table 4 of the paper, and ignoring support settlement.

Again it can be seen that the design loads and end shear forces increased substantially for each of the plastic analysis methods, to the extent that vertical shear capacity again governed the design with membrane action.
Statically indeterminate slabs DSOW-ST3 & ST4 with their ends on rollers were designed using linear elastic analysis or plastic analysis ignoring compressive membrane action, with all the results shown in Table 5 of the paper.

Again it can be seen that the design loads and end shear forces increased substantially based on plastic analysis.
The SRIA commissioned the research to develop the new simplified design rules in AS 3600–2009 for two-way action of rectangular slabs supported on four sides incorporating either Class N or L reinforcement.

Modelling the two-way slab under uniform water pressure during the proof testing stage, in one case it was assumed that all of the edges were continuous and built in. The design live load, $Q$, was calculated as 10.0 kPa.

If a designer doubted that the connection of the test slab to the tubular steel ring beam could provide a level of rotational restraint equivalent to full continuity of the slab over an interior support, then they could assume that the edges were discontinuous. However, this did not affect the result, with $Q$ still 10.0 kPa based on strength.
For Stage B, with the 4 point loads applied in the configuration shown here, and conservatively ignoring any in-plane restraint effects, the slab was designed for local punching shear around each patch load.

It was determined that the design shear capacity of each loaded 200 mm square patch was 184 kN, which was intentionally in excess of any of the design loads calculated to cause flexural failure, and furthermore, it was in excess of the capacity of each jack which was nominally 170 kN. Therefore, punching shear was not a governing design criterion for the set-up as shown.
A simple approach was to design the slab in accordance with Clause 9.6 *Moment Resisting Width for One-way Slabs supporting Concentrated Loads* of AS 3600–2009, with the effective width of each shaded one-way strip calculated as 1400 mm.

Next the slab strips were designed using linear elastic analysis, or plastic analysis ignoring compressive membrane action. The strips could have been designed plastically accounting for compressive membrane action, like for the other restrained slabs, but instead the two-way slab was designed plastically using yield-line theory.
Plastic analysis using yield-line theory was undertaken in accordance with Clause 6.7.3.2 Yield line method for slabs of AS 3600–2009 to model two-way flexural action.
This slide shows the bending moment fields under unit point loads in either the secondary or primary bending directions, determined using finite-element analysis in accordance with Clause 6.4 of AS 3600–2009 to account for two-way flexural action, modelling the slab as a flat plate assuming all four edges fully built-in. In-plane dilation effects were conservatively eliminated, and membrane action was also suppressed. Uncracked concrete was assumed in accordance with Clause 2.2.3(a) of AS 3600–2009.
Strength Design of TW Slab

- Stage B – 4 Point Loads:
  - Linear Elastic, One-Way Strip
  - Plastic, One-Way Strip (ignore membrane act.)
  - Linear Elastic Finite Element Analysis
  - Yield-Line Analysis

<table>
<thead>
<tr>
<th>Strength Design Method</th>
<th>$4P$</th>
<th>$4P = 6P'$</th>
<th>$V_{pl}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear elastic / one-way strip</td>
<td>-45.52</td>
<td>68.28</td>
<td>15.67</td>
</tr>
<tr>
<td>Plastic / one-way strip ignoring compressive membrane action</td>
<td>72.53</td>
<td>108.60</td>
<td>19.43</td>
</tr>
<tr>
<td>Plastic / one-way strip including compressive membrane action</td>
<td>not calculated</td>
<td>not calculated</td>
<td>not calculated</td>
</tr>
<tr>
<td>Finite-element linear elastic / two-way flexural action</td>
<td>51.56</td>
<td>77.34</td>
<td>15.94</td>
</tr>
<tr>
<td>Yield-line analysis / two-way flexural action</td>
<td>153.47</td>
<td>230.20</td>
<td>not calculated</td>
</tr>
</tbody>
</table>

The results of all of these analysis methods applied to the design of the two-way slab are summarised in this table in the paper. Once again, the plastic methods gave much higher design loads and edge shear forces.
In conclusion:

All of the methods of analysis permitted by AS 3600–2009 to be used to design reinforced-concrete slabs incorporating Class L mesh have been described and were investigated.

Some plastic methods of analysis have also been used, particularly to account for compressive membrane action.

This is not to infer that slabs incorporating Class L mesh should be designed allowing moment redistribution at ultimate load. Instead, these methods of analysis have been investigated to potentially model the behaviour of the slabs better than linear elastic analysis.
Question Time

SRIA’s Class L Mesh
Elevated Slab Tests
Scott Munter & Mark Patrick

Part 2A – Strength Design to Concrete Structures Standard AS 3600–2009