

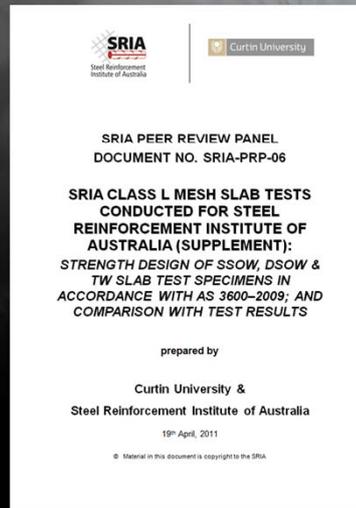


In this presentation, I will cover in more detail the strength design of the test slabs in accordance with AS 3600–2009.

In Part 2B we will compare the design strengths with the test results.

# Supplementary Report

- Strength Design Assessment



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.

## Supplementary Report

- “Unrestrained” slabs
- “Restrained” slabs



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.

## Overview of Part 2A

- Strength Design to AS 3600–2009
- Strength Design of SSOW Slabs
- Strength Design of DSOW Slabs
- Strength Design of TW Slab



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.

## Strength Design to AS 3600–2009

At all potentially critical sections with Class L main bars:

- For bending without compression:

$$\phi M_{uo} \geq M^*$$

$$\text{where } 0.6 \leq \phi (=1.19 - 13k_{uo}/12) \leq 0.64$$

- For vertical shear:

$$\phi V_{uc} \geq V^*$$

$$\text{where } \phi = 0.7$$



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

**Table 1.** Design moment capacity,  $\phi M_{uo}$  in kNm/m & design shear capacity,  $\phi V_{uc}$  in kN/m.

Test Series	Test Specimen No.	$\phi M_{uo,x}^+$ ( $\phi V_{uc,x}^+$ )	$\phi M_{uo,x}^-$ ( $\phi V_{uc,x}^-$ )	$\phi M_{uo,y}^+$ ( $\phi V_{uc,y}^+$ )	$\phi M_{uo,y}^-$ ( $\phi V_{uc,y}^-$ )
SSOW	SSOW-ST1	9.29 (50.74)	7.71 (47.63)	-	-
	SSOW-ST2	7.71 (47.63)	-	-	-
	SSOW-ST3	7.71 (47.63)	-	-	-
	SSOW-ST4	9.29 (50.74)	-	-	-
	SSOW-ST5	14.93 (80.36)	-	-	-
	SSOW-ST6	15.30 (83.48)	-	-	-
	SSOW-ST7	13.50 (78.42)	-	-	-
	SSOW-ST8	14.04 (81.66)	-	-	-
	SSOW-TRIAL	9.29 (50.74)	-	-	-
DSOW	DSOW-ST1	7.71 (47.63)	9.29 (50.74)	-	-
	DSOW-ST2	7.71 (47.63)	9.29 (50.74)	-	-
	DSOW-ST3	7.71 (47.63)	9.29 (50.74)	-	-
	DSOW-ST4	7.71 (47.63)	9.29 (50.74)	-	-
TW	TW-ST1	9.29 (50.74)	7.71 (47.63)	8.21 (48.99)	6.91 (46.15)



This table from the paper summarises all the values of design moment capacity in pure bending,  $\phi M_{uo}$ , calculated ignoring compressive membrane action, and design shear capacity,  $\phi V_{uc}$ , 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.

## Strength Design to AS 3600–2009

- Normal combination of factored actions  $1.2G + 1.5Q$  assumed
- Methods of analysis:
  - static analysis
  - linear elastic analysis
  - finite-element analysis
  - non-linear frame analysis
  - simplified flexural analysis



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.

## Strength Design of SSOW Slabs

- Unrestrained SSOW Slabs (ST2 to ST8 & Trail):

**Table 2.** Strength design of unrestrained SSOW slabs (SSOW-ST2 to ST8 & SSOW-TRIAL).

Test Series	Test Specimen No.	SSOW-ST2, SSOW-ST4 to SSOW-ST8 and SSOW-TRIAL			SSOW-ST3		
		$4P_s^*$ (kN/m)	$4P^* = 6P_s^*$ (kN/m)	$V_{max}^*$ (kN/m)	$P_s^*$ (kN/m)	$P^* = 1.5P_s^*$ (kN/m)	$V_{max}^*$ (kN/m)
SSOW	SSOW-ST2	12.99	19.49	13.38	-	-	-
	SSOW-ST3	-	-	-	6.64	9.96	8.61
	SSOW-ST4	16.59	24.89	16.08	-	-	-
	SSOW-ST5	29.45	44.18	25.72	-	-	-
	SSOW-ST6	30.29	45.44	26.35	-	-	-
	SSOW-ST7	26.19	39.29	23.28	-	-	-
	SSOW-ST8	27.42	41.13	24.20	-	-	-
	SSOW-TRIAL	16.59	24.89	16.08	-	-	-



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  $1.5Q$ ).  $V_{max}^*$  is the corresponding maximum design end shear force.

# Strength Design of SSOW Slabs

- Restrained SSOW Slab (SSOW-ST1):
  - linear elastic analysis;
  - plastic analysis ignoring compressive membrane action; and
  - plastic analysis including membrane action (Park and Gamble)

**Table 3.** Strength design of restrained SSOW slab (SSOW-ST1).

Strength Design Method	$4P'_s$ (kN/m)	$4P' = 6P'_s$ (kN/m)	$V'_{max}$ (kN/m)
Linear elastic	21.00	31.50	19.38
Plastic / compressive membrane action ignored	40.10	60.15	30.08
Plastic / compressive membrane action	63.5	95.25	47.63 (shear controls)

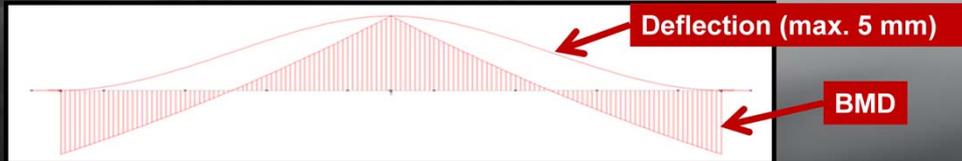


Statically indeterminate slab SSOW-ST1 was designed three ways, with all the results shown in Table 3 of the paper, namely: linear elastic analysis in accordance with Clause 6.2 of AS 3600–2009; plastic analysis ignoring compressive membrane action; and plastic analysis including compressive membrane 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.

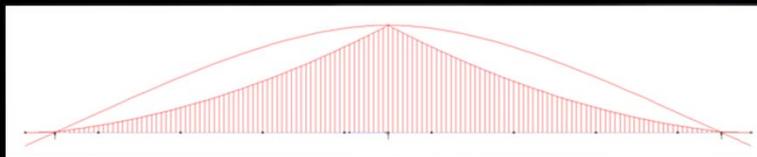
This is despite Clause 6.7 of AS 3600 requiring Class N bars to be used throughout for flexural reinforcement when plastic collapse analysis is used.

## Strength Design of DSOW Slabs

- Support settlement with restrained ends



- Support settlement with unrestrained ends



In both cases the design ultimate moment capacities were well exceeded  $\Rightarrow$  failed, so no reserve capacity for carrying live load



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.

## Strength Design of DSOW Slabs

- Restrained DSOW Slabs (DSOW-ST1 & ST2):
  - linear elastic analysis;
  - plastic analysis ignoring compressive membrane action; and
  - plastic analysis including membrane action (Park and Gamble)

**Table 4.** Strength design of restrained DSOW slabs (DSOW-ST1 & DSOW-ST2).

Strength Design Method	$4P'_s$ (kN/m)	$4P' = 6P'_s$ (kN/m)	$V'_{max}$ (kN/m)
Linear elastic	26.33	39.50	23.38
Plastic / compressive membrane action ignored	38.91	58.37	29.18
Plastic / compressive membrane action	67.7	101.50	50.74 (shear controls)



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.

## Strength Design of DSOW Slabs

- Unrestrained DSOW Slabs (DSOW-ST3 & ST4):
  - linear elastic analysis; and
  - plastic analysis ignoring compressive membrane action

**Table 5.** Strength design of unrestrained DSOW slabs (DSOW-ST3 & DSOW-ST4).

Strength Design Method	$4P_s^*$ (kN/m)	$4P^* = 6P_s^*$ (kN/m)	$V_{max}^*$ (kN/m)
Linear elastic	16.07	24.11	19.74
Plastic / compressive membrane action ignored	25.68	38.52	23.30

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.

# Strength Design of TW Slab

- Stage A – Uniform Water Pressure
  - Simplified Flexural Analysis:
    - four edges continuous; or
    - four edges discontinuous

TABLE 6.10.3.2(B)  
BENDING MOMENT COEFFICIENTS FOR RECTANGULAR SLABS  
SUPPORTED ON FOUR SIDES (DUCTILITY CLASS N  
OR DUCTILITY CLASS L REINFORCEMENT)

Edge condition		Short span coefficients ( $\beta_x$ and $\alpha_x$ )										Long span coefficients ( $\beta_y$ and $\alpha_y$ ) for all values of $L_y/L_x$
		Values of $L_y/L_x$										
		1.0	1.1	1.2	1.4	1.5	1.75	2.0	2.25	2.5	2.75	3.0
1 Four edges continuous	$\beta$	0.021	0.025	0.029	0.032	0.034	0.036	0.039	0.041	0.042	0.026	0.026
	$\alpha$	2.31	2.22	2.14	2.10	2.06	2.03	2.00	2.00	2.00	2.00	2.00
2 One short edge discontinuous	$\beta$	0.027	0.030	0.033	0.035	0.037	0.039	0.041	0.042	0.042	0.024	0.024
	$\alpha$	2.20	2.14	2.10	2.06	2.04	2.02	2.00	2.00	2.00	2.00	2.29
3 One long edge discontinuous	$\beta$	0.024	0.028	0.034	0.038	0.043	0.047	0.050	0.051	0.051	0.028	0.028
	$\alpha$	2.22	2.17	2.09	2.03	1.97	1.93	1.86	1.81	1.80	2.46	2.46
4 Two short edges discontinuous	$\beta$	0.032	0.035	0.037	0.038	0.039	0.040	0.042	0.042	0.042	0.024	0.024
	$\alpha$	2.09	2.05	2.03	2.01	2.00	2.00	2.00	2.00	2.00	2.00	—
5 Two long edges discontinuous	$\beta$	0.024	0.028	0.035	0.042	0.049	0.056	0.071	0.085	0.125	0.039	0.039
	$\alpha$	—	—	—	—	—	—	—	—	—	2.31	2.31
6 Two adjacent edges discontinuous	$\beta$	0.031	0.036	0.041	0.046	0.050	0.053	0.060	0.064	0.070	0.034	0.034
	$\alpha$	2.13	2.07	2.01	1.96	1.92	1.89	1.83	1.80	1.80	2.13	2.13
7 Three edges discontinuous (one long edge continuous)	$\beta$	0.039	0.044	0.048	0.052	0.055	0.058	0.063	0.066	0.070	0.035	0.035
	$\alpha$	2.04	1.97	1.93	1.89	1.86	1.84	1.80	1.80	1.80	—	—
8 Three edges discontinuous (one short edge continuous)	$\beta$	0.033	0.039	0.047	0.054	0.061	0.067	0.082	0.093	0.125	0.046	0.046
	$\alpha$	—	—	—	—	—	—	—	—	—	2.12	2.12
9 Four edges discontinuous	$\beta$	0.064	0.052	0.059	0.066	0.073	0.079	0.091	0.100	0.125	0.049	0.049
	$\alpha$	—	—	—	—	—	—	—	—	—	—	—

Q=10.0 kPa

Q=10.0 kPa



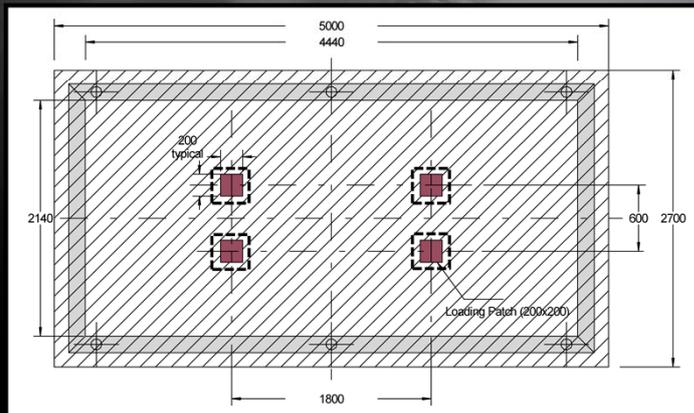
The SRIA commissioned the research to develop the new simplified design rules in AS 3600–2009 for two-way action of rectangular slabs supported on four sides incorporating either Class N or L reinforcement.

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.

## Strength Design of TW Slab

- Stage B – 4 Point Loads:
  - Design for Punching Shear

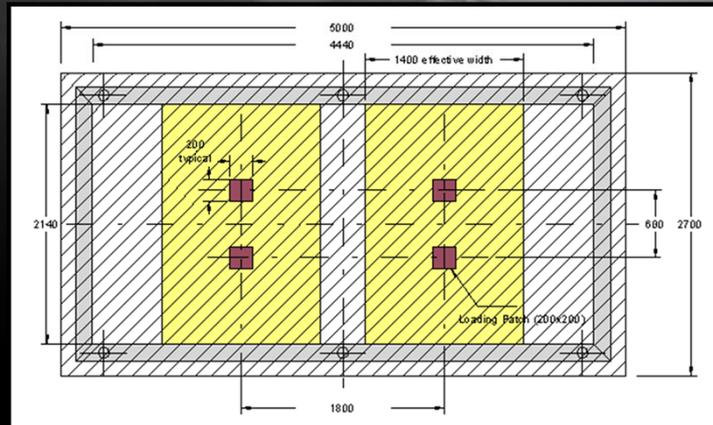


For Stage B, with the 4 point loads applied in the configuration shown here, and conservatively ignoring any in-plane restraint effects, the slab was designed for local punching shear around each patch load.

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.

## Strength Design of TW Slab

- Stage B – 4 Point Loads:
  - Linear Elastic or Plastic, One-Way Strip Design



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.

## Strength Design of TW Slab

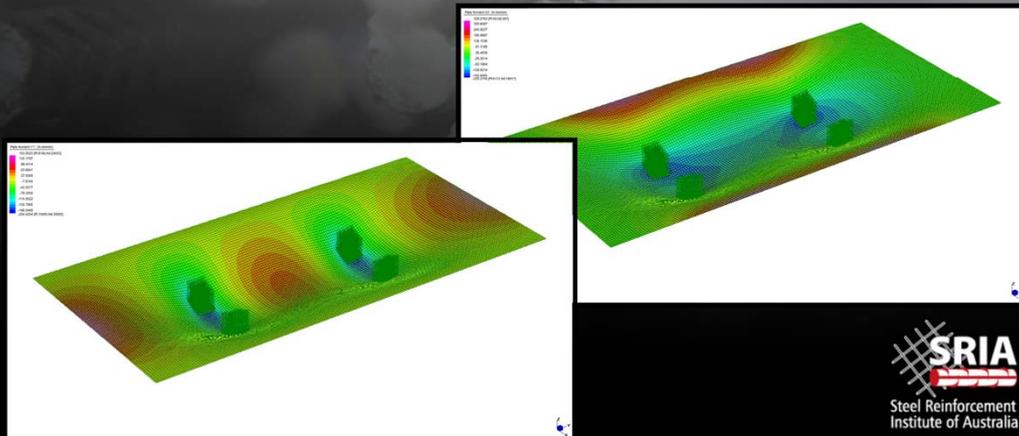
- Stage B – 4 Point Loads:
  - Yield-Line Analysis



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.

## Strength Design of TW Slab

- Stage B – 4 Point Loads:
  - Elastic Finite-Element Analysis



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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 6.** Strength design of restrained TW slab under 4 patch loads (TW-ST1).

Strength Design Method	$4P'_s$ (kN)	$4P' = 6P'_s$ (kN)	$V'_{max}$ (kN/m)
Linear elastic / one-way strip	45.52	68.28	15.57
Plastic / one-way strip ignoring compressive membrane action	72.53	108.80	19.43
Plastic / one-way strip including compressive membrane action	not calculated	not calculated	not calculated
Finite-element linear elastic / two-way flexural action	51.56	77.34	15.94
Yield-line analysis / two-way flexural action	153.47	230.20	not calculated



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.

## Conclusions to Part 2A

- Strength Design to AS 3600–2009
- Strength Design of SSOW Slabs
- Strength Design of DSOW Slabs
- Strength Design of TW Slab



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