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Structural Ductility of Edge-supported Two-Way Slabs Reinforced with Low-Ductility Steel

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ABSTRACT

This paper describes a series of full range load tests on two-way, edge-supported reinforced concrete slab panels containing either Class L WWF or Class N deformed bars. Five rectangular slab panels were tested each with two free edges and two adjacent edges continuously supported. A point support was included under the corner of each panel at the intersection of the two free edges. Each slab specimen was loaded by four transverse loads applied symmetrically in the mid-panel region by a deformation controlled actuator in a stiff testing frame. The continuous edge supports were provided by clamping two adjacent edges in a carefully designed and constructed testing frame. The slabs were instrumented with load cells to measure applied forces and reactions, strain gauges to measure strain in the steel reinforcement and on the concrete surfaces, linear variable displacement transducers and lasers to measure deflections at all stages of loading. The results of the tests are presented and evaluated, with particular emphasis on the strength, ductility and failure mode of the slabs.

1. INTRODUCTION

Ductility is a measure of the ability of a structural element or system to sustain plastic deformations before collapse, without substantial loss of load resistance (Warner et al. 1998). Ductility is an essential property of concrete structures and many of the assumptions made routinely in their analysis and design depend on the structure being ductile. Ductility allows for redistribution of internal forces from highly stressed regions to less stressed areas, so that structures can develop the full strength of the critical sections considered in design. On the other hand, brittle structures may not be able to do so. Ductile structures experience relatively large deformations before failure and this provides warning of impending failure prior to collapse. Ductility also provides robustness and resilience in dissipating the internal energy generated by loading.

The trend in the construction industry to provide more cost effective materials has led to the use of higher strength reinforcing steel and concrete, fiber reinforced

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polymers (FRP), fiber reinforcement and high-strength strands. Unfortunately, the use of such materials had an adverse impact on the ductility of reinforced concrete structures (Ho Park 2017, Bank 2013, Ma *et al.* 2016, Mousa 2015, Wang and Belarbi 2011, Dancygier and Berkover 2016, Sakka 2009, Mohammadhassani *et al.* 2013).

The ductility of reinforcing steel is usually specified in terms of its minimum elongation at maximum force (ε_u) and the minimum tensile strength to yield stress ratio (f_{su}/f_{sy}). The term ε_{su} is the minimum permitted value for the strain at peak stress, corresponding to the onset of necking (Gilbert and Sakka 2007). For low ductility steel (Class L in Australia and Class A in Europe), the Australian code (AS3600-2009) specifies a minimum value of ε_{su} = 1.5%, whereas the minimum value in Europe is ε_{su} = 2.5%. Low-ductility reinforcement in the form of cold-worked welded wire fabric with ε_u in the range 1.5–3.5% is quite brittle, yet its use is permitted in suspended floor slabs for new and existing structures by many national standards, albeit with certain restrictions.

Concrete slabs usually have small flexural reinforcement ratios and are generally considered very ductile structural members. However, the use of low ductility reinforcing steel in the form of welded wire mesh in one-way slabs loaded to failure has been shown to produce sudden and catastrophic failures caused by fracturing of the tensile reinforcement with very little plastic deformation prior to collapse (Gilbert 2005; Gilbert and Smith 2006; Gilbert and Sakka 2007; Gilbert et al. 2006, 2007, Gilbert and Sakka 2009, Gilbert and Sakka 2010, Munter and Patrick 2012a, 2012b). As a result of this work, the Australian Standard AS3600-2009 reduced the strength reduction factor for flexural elements from ϕ = 0.8 for members containing normal ductility steel reinforcement (with $\varepsilon_{su} \geq 5\%$) to ϕ = 0.64 for member containing low-ductility (Class L) reinforcement. This decision has been vindicated for one-way (Foster and Kilpatrick 2008; Sakka and Gilbert 2008a, 2008b, 2008c; Goldsworthy et al. 2009; Tuladhar and Lancini 2014) and two-way (Sakka and Gilbert 2017, 2018) slabs by experimental and theoretical work.

This paper presents the results of full range load tests on two-way, edge-supported reinforced concrete slab panels containing either Class L WWF or Class N deformed bars. Five rectangular slab panels were tested each with two free edges and two adjacent edges continuously supported. The slabs were instrumented with load cells, strain gauges, linear variable displacement transducers (LVDT's) and lasers.

2. EXPERIMENTAL PROGRAM

2.1 Test Specimens

Five rectangular two-way concrete slabs with two adjacent edges that were fully supported and restrained were tested in this phase of the research. Two adjacent edges were clamped and were completely restrained from vertical displacements and partially restrained from rotational displacements. The other two edges were free with a roller point support located at the corner where the two free edges intersect. The roller point support was provided in an attempt to minimize the development of membrane actions while testing. Fig. 1 shows a schematic diagram of the boundary conditions of the test specimens.

The slab specimens had overall dimensions of 2400mm x 3600mm. After clamping two adjacent edges of the slab using a specifically designed steel frame, the plan dimensions of the slabs became 1590mm x 2790mm with clear spans of 2570mm x 1370mm, as shown in Fig. 1. In total, five slabs with different types and ratios of reinforcement were tested. Two types of steel reinforcements were used; Class L WWF and Class N deformed bars. Fig. 2 shows cross sections through a typical specimen and the reinforcement arrangement in the edge-supported two-way slab specimens.
A local system of x-y axes was adopted for the slabs; as shown in Fig. 1. The origin of the coordinate system is located 1,395mm from the free short edge (in the x-direction) and 160mm from the long free edge (in the y-direction), as shown. Each slab had two layers of orthogonal bars or wires (in the form of either Class L welded wire fabric or Class N deformed bars), one layer near the top surface and one layer near the bottom surface and each layer of orthogonal reinforcement had bars or wires running in both the x and y directions, with a different effective depth, d_x or d_y in each direction, as shown in Fig. 2. The *x* and *y* scripts represent the direction (axis) of the relevant bars or wires. Table 1 lists the dimensions and reinforcement of each slab while Table 2 summarizes the properties of the concrete and Table 3 summarizes the properties of the reinforcement. The top and bottom reinforcement layouts in the test specimens are shown in Fig. 3. All the dimensions shown in the figures are in millimetres.

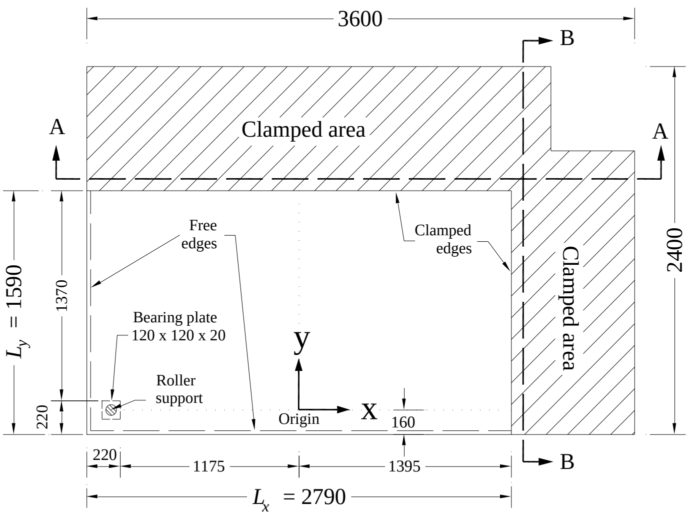


Fig. 1 Schematic diagram for the boundary conditions of the two-way slabs.

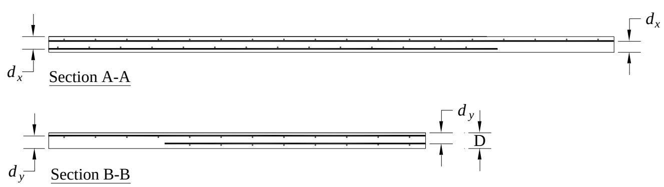
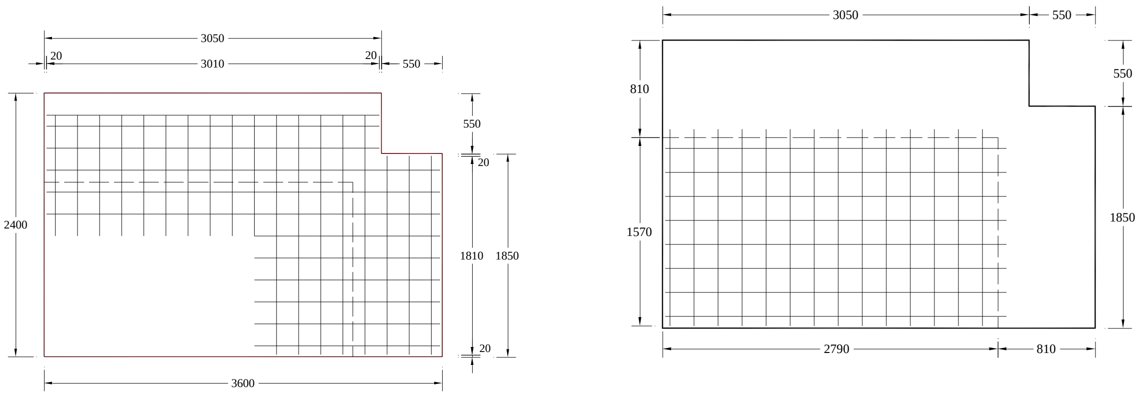


Fig. 2 Cross sections of the tested slabs and reinforcement arrangement.



(a) (b)

Fig. 3 Distribution of (a) top reinforcement mesh and (b) bottom reinforcement mesh.

Table 1 Properties of the edge supported two-way slab specimens.

					X Direction				Y Direction			
Slab Name	L_x[a] *(mm)*	L_y[a] *(mm)*	D[b] *(mm)*	*Steel*	n[c]	A_{st} *(mm²)*	d_x *(mm)*	*p (%)*	n[b]	A_{st} *(mm²)*	d_y *(mm)*	*p (%)*
C2R-1	2630	1430	100	Bot.	8	363	86.7	0.26	14	635	79.1	0.29
				Top	8	363	59.7	0.38	14	635	71.7	0.32
C2R-2	2630	1430	100	Bot.	8	567	84.5	0.42	14	992	75.0	0.47
				Top	8	567	67.2	0.53	14	992	75.4	0.47
C2R-3	2630	1430	100	Bot.	8	628	80.0	0.49	14	1100	70.0	0.56
				Top	8	628	68.0	0.58	14	1100	78.0	0.51
C2R-4	2630	1430	100	Bot.	8	567	79.6	0.45	14	992	70.1	0.51
				Top	8	363	77.7	0.29	14	635	87.3	0.26
C2R-5	2630	1430	100	Bot.	5	393	88.6	0.28	8	628	78.6	0.29
				Top	5	393	63.8	0.39	8	628	74.9	0.30

[a] Clear span
[b] measurements are within ± 5 mm
[b] n = number of bars or wires

Table 2 Concrete properties of the tested edge supported slabs.

Slab Name	f'_c *(MPa)*	ε_{cu} *(%)*	f_t *(MPa)*	f_{cf} *(MPa)*	E_c *(GPa)*
C2R-1	46.8	0.244	3.87	4.75	32.58
C2R-2	46.8	0.244	3.87	4.75	32.58
C2R-3	43.1	0.22	4.03	4.64	28.54
C2R-4	43.1	0.22	4.03	4.64	28.54
C2R-5	44.0	0.292	3.56	4.60	28.29

Table 3 Steel properties of the tested edge supported slabs.

Slab Name	*Steel*	*Steel Type*	*Dia. (mm)*	E_s	f_y *(MPa)*	f_u *(MPa)*	f_u/f_y	ε_{su} *(%)*
C2R-1	Bot.	SL82	7.6	2 x10^5	602	673	1.12	2.77
	Top	SL82	7.6	2 x10^5	606	669	1.10	2.50
C2R-2	Bot.	SL102	9.5	2 x10^5	518	579	1.14	3.73
	Top	SL102	9.5	2 x10^5	596	632	1.06	3.41
C2R-3	Bot.	N10	10.0	2 x10^5	565	677	1.20	9.65
	Top	N10	10.0	2 x10^5	565	677	1.20	9.65
C2R-4	Bot.	SL102	9.5	2 x10^5	609	660	1.08	3.64
	Top	SL82	7.6	2 x10^5	571	630	1.10	2.45
C2R-5	Bot.	N10	10.0	2 x10^5	606	694	1.15	7.25
	Top	N10	10.0	2 x10^5	606	694	1.15	7.25

2.2 Test Setup

A steel frame was designed and fabricated to continuously support two-adjacent edges of the specimen and to clamp the concrete slab along these two edges from both the top and bottom surfaces to provide restraint against rotation. Fig. 4 shows front and rear views of the test setup. More details about the test setup are provided in the next section. The clamped portion of the slab was an extension of the slab past the face of the continuous support by a distance of 810 mm in each direction, as shown in Fig. 5. The length of the clamped portion of the slab was selected to ensure that the top reinforcement in the critical negative moment region at the face of each continuous support was fully developed. The load was applied to the slabs through four steel bearing plates as shown in Fig. 5.

(a) Front view.

(b) Rear view.

Fig. 4 Test setup showing test frame for the two-way slab tests.

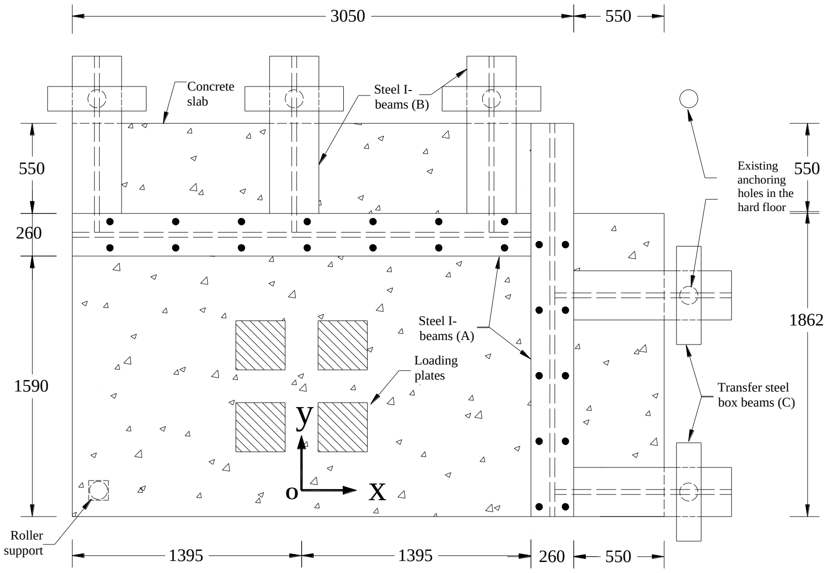


Fig. 5 Schematic plan view of the testing setup.

2.3 Instrumentation

Reactions were measured using 13 load cells as shown in Fig. 6. In addition, strain gauges were placed on the concrete surface and on the reinforcing steel wires to measure strains and their locations are show in Fig. 7. LVDTs, lasers, and dial gauges were placed on different locations of the tested slabs to measure displacements and rotations and their locations are shown in Fig. 8.

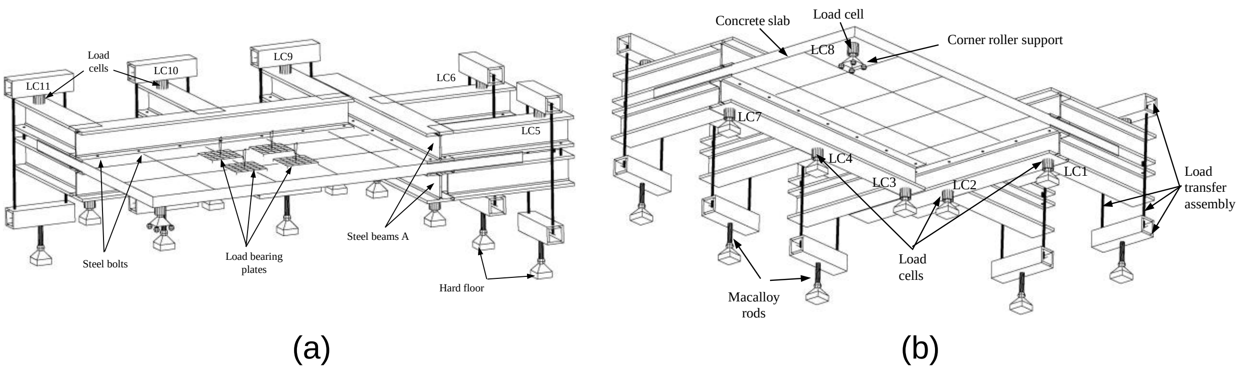


Fig. 6 Testing setup for the continuous two-way slabs (a) front top isometric view, (b) front bottom isometric view.

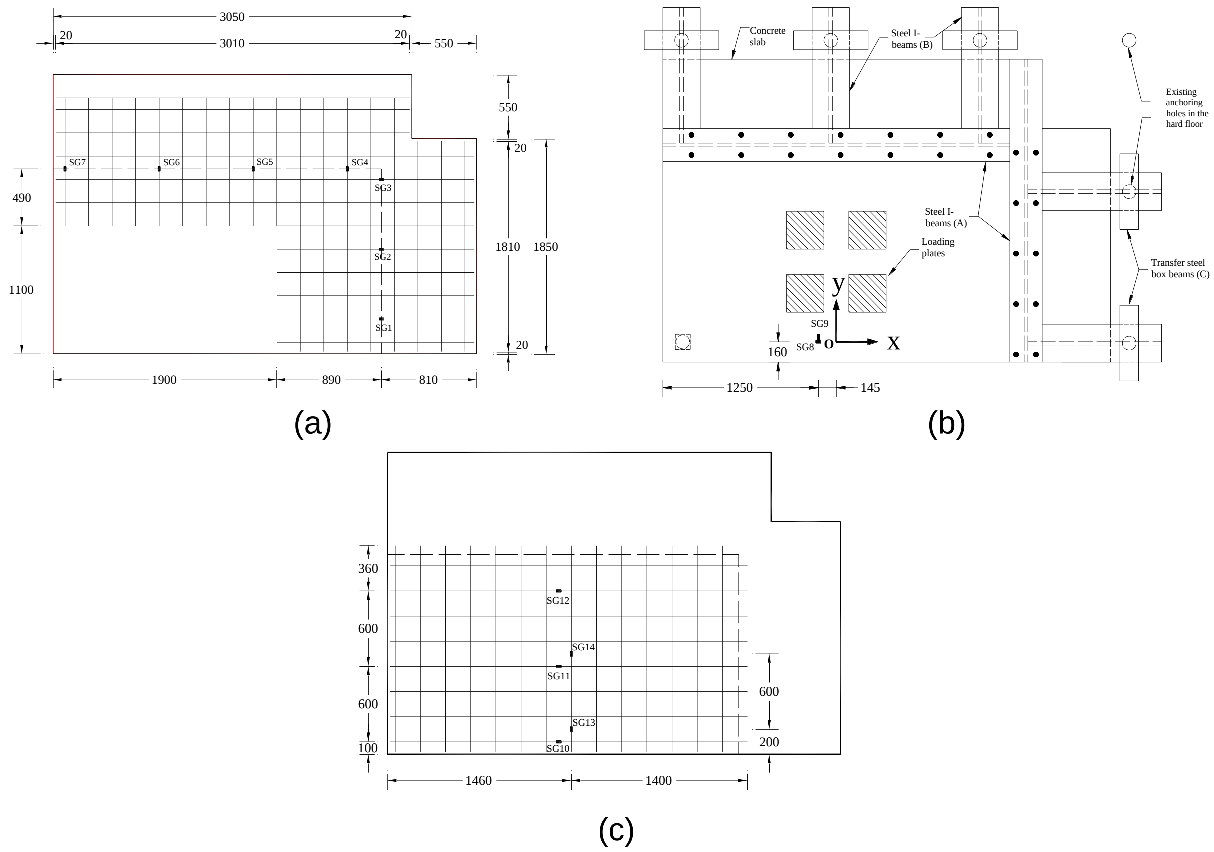


Fig. 7 Location of the strain gauges on (a) the top reinforcing wires, (b) the concrete surface and the concrete surface.

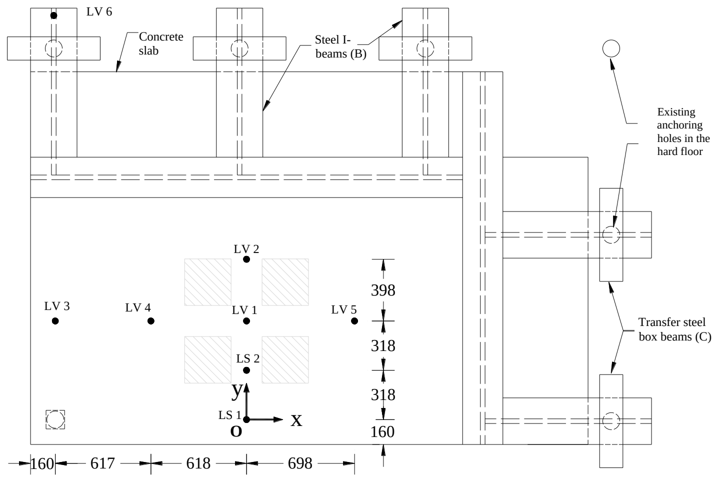


Fig. 8 Location of the LVDTs and the lasers used to measure deflections.