# Performance of Slabs with varying Reinforcement Configurations

Royce Newton[1], Aaron Beecroft[1], Cameron Maher[1] and Natalie Lloyd[2]
[1] Undergraduate Student, Curtin University
[2]Senior Lecturer, Curtin University

**Synopsis**: The subject of ductility of suspended slabs constructed with Class L mesh as primary reinforcement led to widespread industry discussion over recent years which led to the current provisions in Australian Standard 3600 - Concrete Structures (2009) [1] which outlines the analysis, design and detailing of such slabs. The aim of this research program was to examine the behaviour – in terms of ultimate strength and ductility parameters - of simply supported one way reinforced concrete slabs with differing reinforcement types with relatively consistent tensile steel reinforcing ratios of the order of 0.4%. Eight slabs were constructed with a range of reinforcing including (i) class L mesh only, (ii) class N reinforcing bar only, (iii) combination of L class mesh and N class bar or (iv) reinforcing consisting of two layers of class L mesh. The classification of the reinforcing is in accordance to Australian and New Zealand Standard 4671 – Steel Reinforcing Materials (2001) [2]. The behaviour of slabs reinforced with L class mesh and steel fibre reinforced concrete was also investigated. This paper presents the test data for 8 test slabs. Four of the slabs were duplicate tests; Control 1 and Control 2 had the same reinforcing arrangement consisting of mesh SL 102; and CS2 and N10 slabs both had 4 N10-220 in both directions of slab. The testing of duplicate tests enabled an assessment of the variability of test data and sensitivity of the ductility parameter $W_1/W_0$.

**Keywords**: ductility, class L mesh, class N bar, steel fibre reinforced concrete, one-way slab,

## 1. Introduction

Slabs are considered ductile if they have the ability to undergo large plastic deformation prior to failure. It is suggested that the use of Class L mesh leads to strain localisation in the steel, which forms a small hinge length leading to small deflections and premature failure [2]. A means of assessing the ductility is by assessing the moment-curvature relationship of a flexural member. Alternatively, the energy absorbed by a flexural member in its pre and post yield stages of loading may be used. The energy absorbed may be taken as the integral of the load-deflection curve. The ductility ratio of a structural element is an indication of its ductility and may be calculated as the ratio of $W_1/W_0$ where $W_0$ represents the work absorbed prior to the yielding of the reinforcement with a corresponding deflection $\Delta_1$. $W_1$ represents the work absorbed between the point of steel yielding and either the reinforcement fracturing or the slab unloading to 75% of its peak value (observable for ductile slabs and/or some loading conditions), with a corresponding deflection of $\Delta_2$ [4,5]. As the point of yielding of the reinforcing may be challenging to discern, the load at which yield will occur may be taken to be equal to the peak load multiplied by $1/(f_{su}/f_{sy})$, where the strength of the steel is the strength of that which is closest to the tensile face, as used by Gilbert [4,5 ]. The points, $\Delta_1$ and $\Delta_2$ are then used to calculate the area under the load-deflection curve to determine $W_0$ and $W_1$ where $W_0$ is the area under the curve between the start of the load deflection plot and $\Delta_1$ and $W_1$ is the area under the curve between $\Delta_1$ and $\Delta_2$. The ratio of $W_1/W_0$ is an indication of a slab's ductility, with a higher ratio corresponding to a more ductile slab. This methodology has been used to assess the ductility parameter of the slabs tested.

## 2. Research Programme

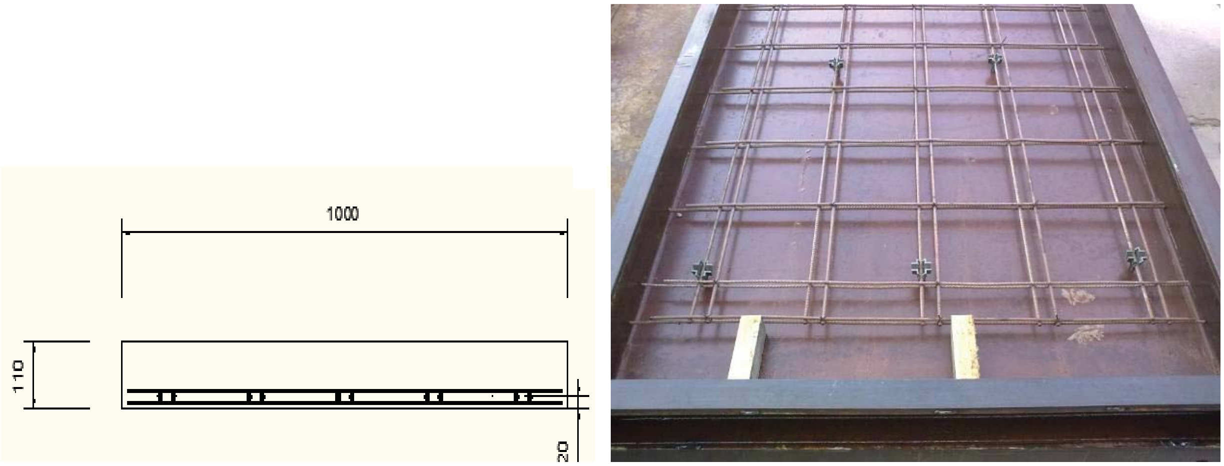
### *2.1 Slabs General Arrangement*

The team of undergraduate researchers constructed and tested eight reinforced, simply supported one-way slabs, the geometry and general reinforcement properties of the slabs were as shown in Table 1. The slabs all had overall length L = 2700mm, width b = 1000mm, nominal overall depth D=110mm and nominal cover to the outermost bars of the reinforcement was 20 mm. Figure 1 shows the reinforcing arrangement for slab SL72 which had 2 layers of SL72 mesh, the reinforcing layout is shown in plan and cross section in Figure 2 for the remaining slabs. The height of the reinforcement from the slab formwork was measured prior to casting and was found to be 20 ± 1 mm. In the case of the slab CS1 the cover was 18 mm to the N class bar and 28 mm to the longitudinal mesh bar. The depth to the centroid of the longitudinal steel is shown in Table 1 calculated from the measured height of reinforcement from the formwork and the nominal slab depth D = 110 mm. All slabs had a longitudinal tensile steel reinforcement ratio ($A_{st}/bd$) of approximately 0.4% and span (center to centre of supports 2290 mm) to depth ratio of approximately 27.

Note that Control 1 and Control 2 were the slabs reinforced with class L mesh only and were duplicate slabs. The slabs CS2 and N10 were the slabs reinforced with class N reinforcing bars (N10-220) to provide duplicate slabs with a similar reinforcing ratio to the mesh reinforced control slabs.

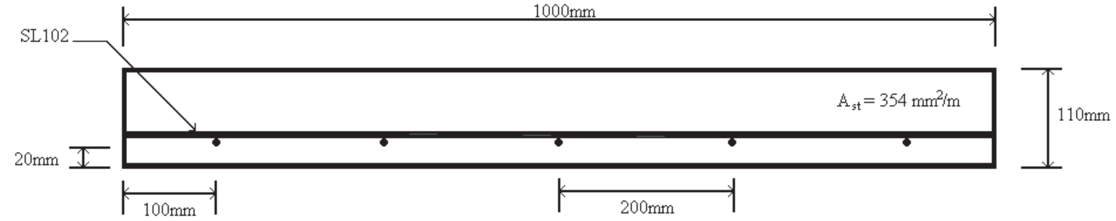
**Table 1. Slab Details**

| Slab Test Date | Slab Notation | Section Nominal Dimensions | | Concrete Steel Fibre Specification | Tension Reinforcement | | |
|---|---|---|---|---|---|---|---|
| | | Width $b$ (mm) | Depth $D$ (mm) | | Type and configuration | Nominal $A_{st}$ ($mm^2$) | d (mm) |
| 30/06/09 | Control 1 | 1000 | 110 | Nil | SL 102 | 354 | 86±1 |
| 7/07/09 | Control 2 | 1000 | 110 | Nil | SL102 | 354 | 85±1 |
| 2/07/09 | Fibre 1 | 1000 | 110 | 30 kg/$m^3$ | SL102 (as per Control 1 and 2 | 354 | 85±1 |
| 2/07/09 | Fibre 2 | 1000 | 110 | 40 kg/$m^3$ | SL102 (as per Control 1 and 2) | 354 | 85±1 |
| 3/07/09 | CS1 | 1000 | 110 | Nil | SL72 + 2 N10-300 tied below the SL72 | 179 + 157 = 336 | 87±3 for N bar<br>78±3 for SL72 |
| 3/07/09 | CS2 | 1000 | 110 | Nil | N10-220 in both directions of slab | 314 | 86±1 |
| 6/07/09 | N10 | 1000 | 110 | Nil | N10-220 in both directions of slab | 314 | 85±1 |
| 6/07/09 | SL72 | 1000 | 110 | Nil | 2 layers of SL72 offset by 30 mm | 157 + 157 = 314 | 86±2 |

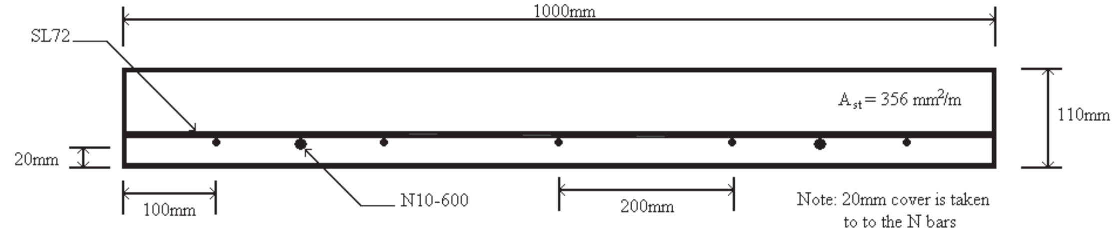


(a) Cross section (b) Reinforcement in Formwork

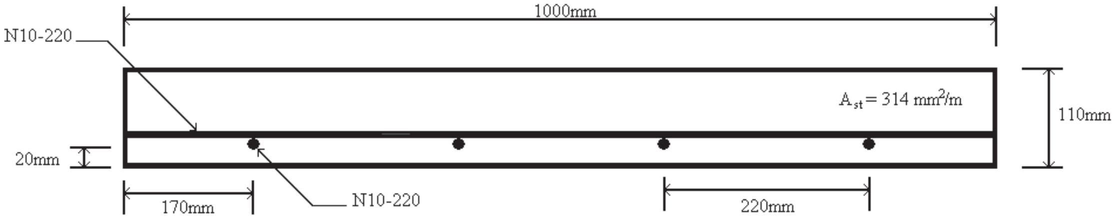
**Figure 1. Slab SL72 (two layers of mesh)**



Typical Cross Section of the Control Slabs



Cross Section of the Slab with SL72 and 2N10's (CS1)



Cross Section of the Slab with N10's in the form of the SL102 Mesh (CS2)

**Figure 2. Slabs Cross Sections.**

## *2.2 Casting and Curing*

All slabs were constructed with a ready mixed concrete with nominal grade of 25 MPa concrete, 80 mm slump and maximum aggregate size of 20 mm. All slabs and associated compression and tension cylinders, except for two slabs; Fibre 1 and Fibre 2, were cast first. The steel fibre used in the concrete was a hook ended high tensile steel fibre with an aspect ratio of 80 and a length of 60mm. After the first 6 slabs were cast, a predetermined mass of the steel fibre to dose the remaining concrete in the truck to nominally 30kg/m$^3$ was added via hopper and dispersed by rotating the truck drum for a recommended 4 minutes. The slab denoted “Fibre 1” was then cast along with test compression and tension cylinders. Further steel fibre was added to the remaining concrete in the truck to achieve a nominal dosage of 40 kg/m$^3$ and slab “Fibre 2” and compression and tension cylinders were cast. Hence, all slabs were cast from the same concrete with or without additional steel fibres. The slabs were cured in ambient conditions and kept moist for 7 days at which time they were stripped from the moulds, lifted using strong backs and stored under cover in the laboratory until tested. Concrete data is presented in Table 2 and discussed in section 2.3.

## *2.3 Steel Reinforcing and Concrete Data*

The fibre content of the concrete was determined by weighing the steel fibres (extracted by sieving, washing and using magnets) for a known volume of concrete (a tensile cylinder). Three fibre content tests were conducted for each dose rate and the averages are presented in Table 2. The actual dose rates were approximately 20 and 30 kg/m$^3$. The compressive and tensile strengths of the concrete were monitored throughout the curing process and testing period of all slabs. The 28 and test day concrete compressive and tensile strengths are presented in Table 2, the compressive strength at time of testing the slabs ranged from 28 to 30 MPa. Tensile tests were conducted on the reinforcing meshes and bars used in the slabs; a minimum of three steel specimens were tested to acquire the steel's average yield and ultimate strengths. The results are shown in Table 3 along with corresponding specifications from AS/NZ 4671 [2]. It should be noted that all reinforcing was commercially sourced and exceeds the minimum requirements of AS/NZ 4671; reinforcing with lower ductility could still be compliant with the code.

**Table 2. Concrete Data**

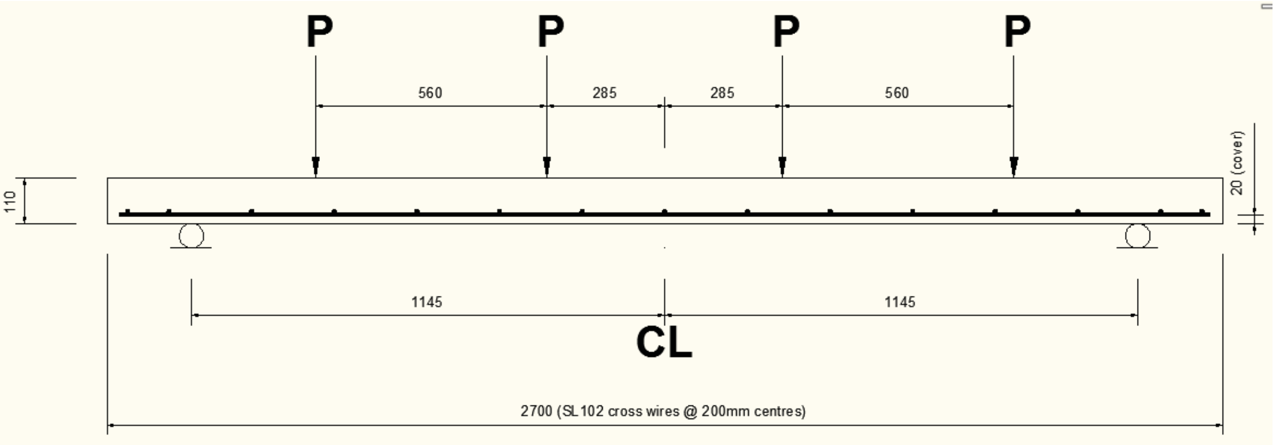
| Concrete Data | | Fibre Content Data | | | |
|---|---|---|---|---|---|
| Property | Value | | Test Cylinder | Mass of Fibre (g) | Dosage ($kg/m^3$) |
| Slump | 160 mm | Fibre 1 Slab | 1 | 87 | 16.4 |
| Compressive Strength $f_{cm}$, 28 day | 26 ±2 MPa | Fibre 1 Slab | 2 | 115 | 21.7 |
| Indirect Tensile Strength 28 day | 2.8 ±0.4 MPa | Fibre 1 Slab | 3 | 108 | 20.4 |
| | | Fibre 1 slab | | | Average 19.5 |
| Compressive Strength $f_{cm}$, 34 day, First Test Slab Control 1 | 28 ±2 MPa | Fibre 2 Slab | 1 | 159 | 30.0 |
| Compressive Strength $f_{cm}$, 36 day Slab Fibre 1 and Fibre 2 | 29 ±2 MPa | Fibre 2 Slab | 2 | 155 | 29.2 |
| Compressive Strength $f_{cm}$, 41 day Last Test Slab Control 2 | 30 ±2 MPa | Fibre 2 Slab | 3 | 156 | 29.4 |
| | | Fibre 2 Slab | | | Average 29.6 |

**Table 3. Steel reinforcing Test Details**

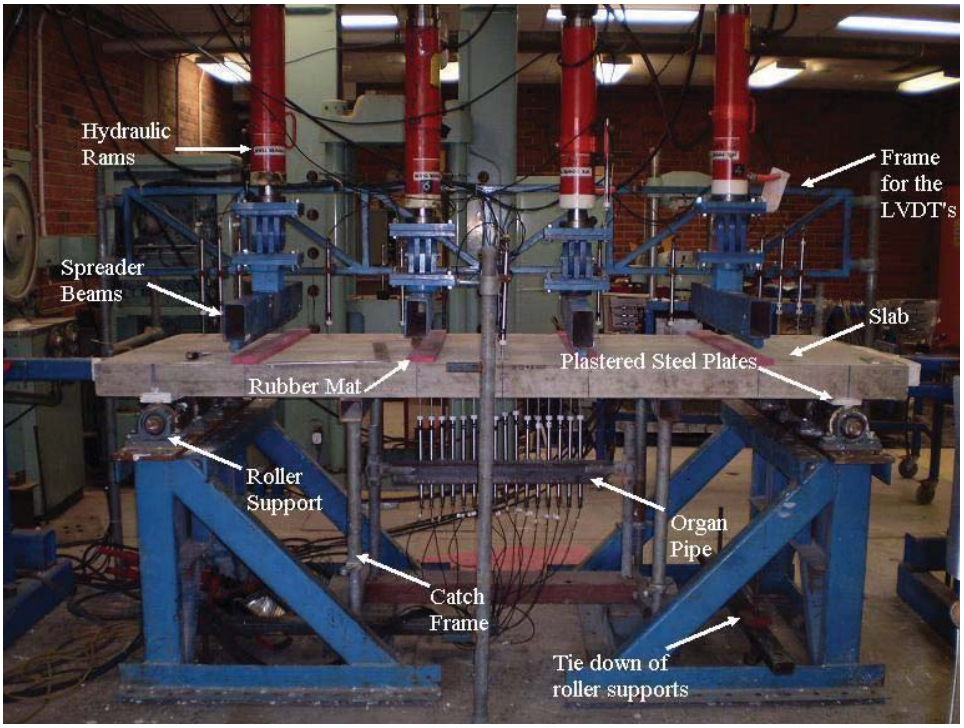
| Property | | Reinforcing | | | AS/NZ 4671 specification | |
|---|---|---|---|---|---|---|
| | | SL102 | SL72 | N10 | L | N |
| Nominal Diameter (mm) | Φ | 9.5 | 6.75 | 10 | 5-16 | 10-40 |
| Yield Stress (MPa) | $f_y$ | 510±10 | 504±12 | 510±6 | 500 | 500 |
| Ultimate Stress (MPa) | $f_u$ | 620±10 | 653±12 | 647±6 | 750 | 650 |
| Tensile Stress to Yield Stress ratio | $f_y/f_u$ | 1.2±0.2 | 1.3±0.3 | 1.3±0.3 | 1.03 | 1.08 |
| Uniform Elongation (%) | $\varepsilon_{su}$ | 1.9±0.9 | 3.4±2 | 8.2±2 | 1.5 | 5.0 |

## *2.4 Loading*

Loads were applied to the slabs via spreader beams spaced at 560mm centres as shown in Figure 3. The slabs were placed on two roller supports and plastered on to the rollers. The slabs all underwent four stages of loading with multiple cycles within each stage; Stage 1 had four cycles of loading/unloading with an individual jack loads of 4kN corresponding to 40% of the ultimate factored capacity of the control slabs and below calculated cracking moment. Stage 2 had ten cycles of loading/unloading with individual jack loads of around 6.5kN (the actual peak load for stage 2 was the load at which flexural cracks were first observed, the value of 6.5kN corresponds to the calculated cracking moment for the slabs). Once the slab first cracked, the load was held steady and crack gauges were applied to the slab. Stage 3 had three cycles of an individual jack load of 11kN as cracks developed and were monitored. Stage 4 had load applied until slab failure and collapse of the slabs (either the fracturing of reinforcement or excessive deflection requiring the load to be released). For the slabs with N class reinforcing bar a judgment was made on when to terminate testing due to excessive deflections based on rotation of the slab on the rollers and protection of the LVDTs below the slab. Typical load-time profiles are shown in Figure 4 for Control 1 (slab with mesh only) and in Figure 5 for Slab CS2 (slab with N10 bar only). To record the deflected profiles of the slabs, linear variable differential transformers (LVDT's) were placed along the slab span on top of the slab to record the slabs overall deflected shape, whilst beneath the slab they were placed along the 500mm mid-span region in an organ pipe configuration to record the deflection profile.



(a) Load and Support Dimensions (Reinforcing shown for Control Slab)



(b) Photo of typical test set-up

**Figure 3. Slab Loading Arrangement.**

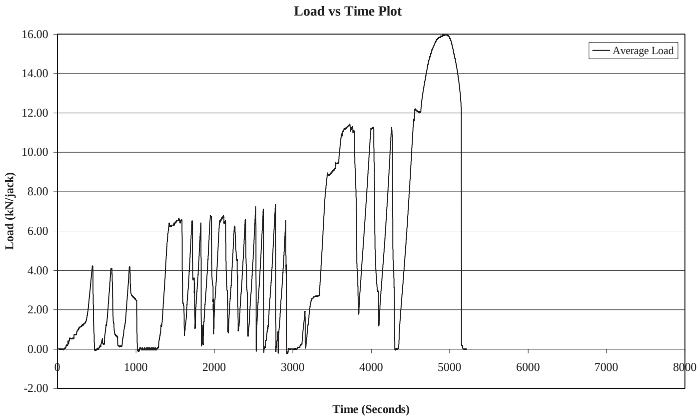


**Figure 4. Slab Loading for Control 1 (Slab with Mesh Only) (Load per Jack, kN).**

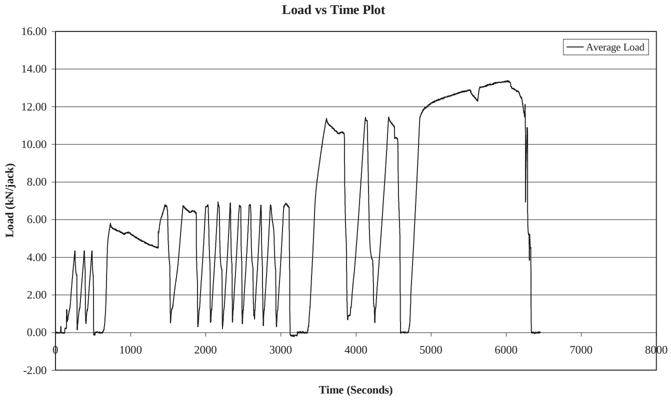


**Figure 5. Slab Loading for CS2 (Slab with N10 bar Only) (Load per Jack, kN).**

## *2.5 Ultimate Capacity, Failure Mode and Strain*

The test ultimate loads and corresponding moments for the slabs are shown in Table 4 along with the ratio of factored moment capacity to the test capacity. The factored moment capacity was determined using stress block parameters and capacity reduction factors of AS 3600 (2009) and actual or measured material properties, including concrete density, steel and concrete properties (Tables 2 and 3) and measured slab geometry [1,6]. For the slab with mixed L class and N class reinforcing (CS1) a capacity reduction factor of 0.6 was applied to all the reinforcing although an alternative approach has been suggested [7].

**Table 4. Theoretical and Test Moment Capacities**

| | Moment $M_u$ (kNm) | $\Phi M_u$ (kNm) | $\Phi M_u / M_u$ |
|---|---|---|---|
| Control One | 20 | 11 | 1.8 |
| Control Two | 19 | 11 | 1.7 |
| Fibre One | 21 | 11 | 1.9 |
| Fibre Two | 21 | 11 | 1.9 |
| CS1 | 18 | 11 | 1.6 |
| CS2 | 18 | 13 | 1.4 |
| N10 | 19 | 13 | 1.5 |
| SL72 | 18 | 9 | 2.0 |

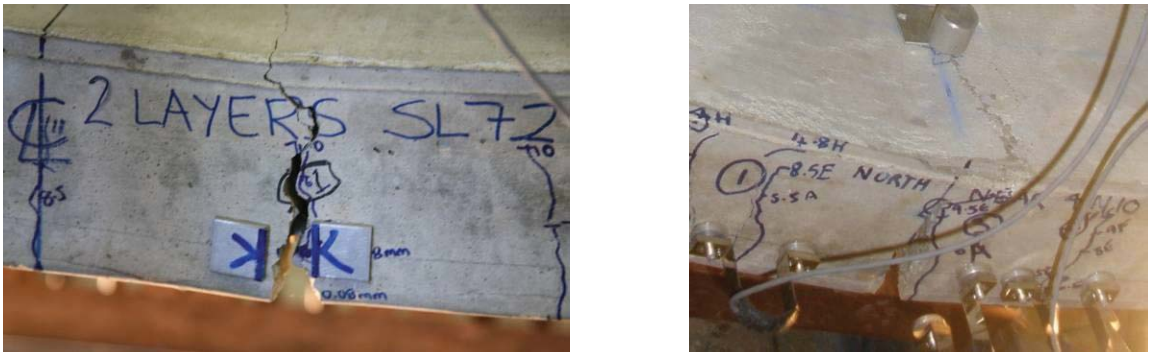
The slabs reinforced with only Class L mesh, Control 1 and Control 2, failed with fracture of the reinforcing bars observed as shown in Figure 6 (a) and (b). The fibre reinforced slabs exhibited typical steel fibre bridging of the flexural cracks as shown in Figure 6(c). The slab with mixed reinforcing; that is, L class mesh and N class reinforcing bar, slab CS1, had concrete crushing on the compressive face and failed due to excessive deflection rather than collapse even after the mesh bars fractured. The slab had more cracks, had more evenly distributed cracks and no single dominant crack throughout the loading stages ; this is unlike the slabs of Control 1 and Control 2. All cracks were found to be opening and closing with the loading cycles throughout testing until just before the maximum load was reached and one crack grew to a point where the mesh fractured and the normal ductility bars remained intact.

(a) Control 1 (Mesh Only)

(b) Typical Fracture of Mesh Bars Observed

(c) Fibre 1 Slab

(d) CS1 mixed SL 72 and N 10 bar



(d) SL72 (2 layers Mesh Only)

(e) N10 (N10 bar only)

**Figure 6.** **Failure of Selected Typical Slabs**

The slab with two layers of mesh, SL72, is shown is Figure 6(d) and in Figure 6(e) one of the slabs with only N class reinforcing bar is shown; these slabs did not fail due to fracture of the bars but due to excessive deflection at which time the loading was ceased. Typical mid span load-deflection profiles are shown in Figure 7 for the Control slabs and also N10 (slab with only N10 bars) and SL72 (slab with two layers of SL72 mesh).

Strain gauges were applied to the mesh and bars of the research slabs. There is insufficient room to present all the data here; however, gauges in Control 2 indicated that the strain at the failure crack was five times that of the strain at a location 100-115mm away. This was not the case in CS2, where the bars were of Class N and were tied in the mesh arrangement, not welded. It was also shown that when mixed reinforcing is used (L class mesh and N class bar) the bars of the mesh failed progressively (not all failing simultaneously).

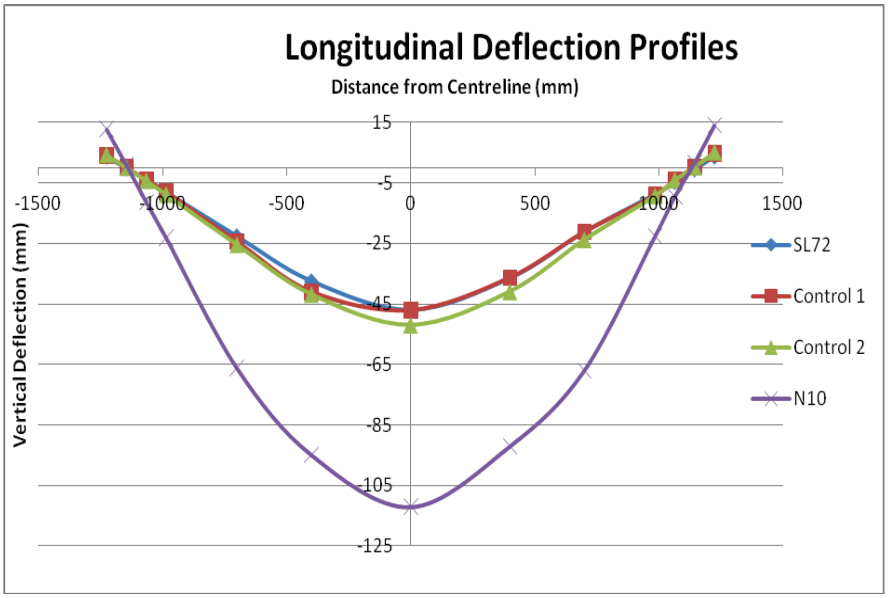


**Figure 7. Longitudinal Load deflection profile of Selected Typical Slabs**

## *2.6 Work Absorbed as a Measure of Ductility*

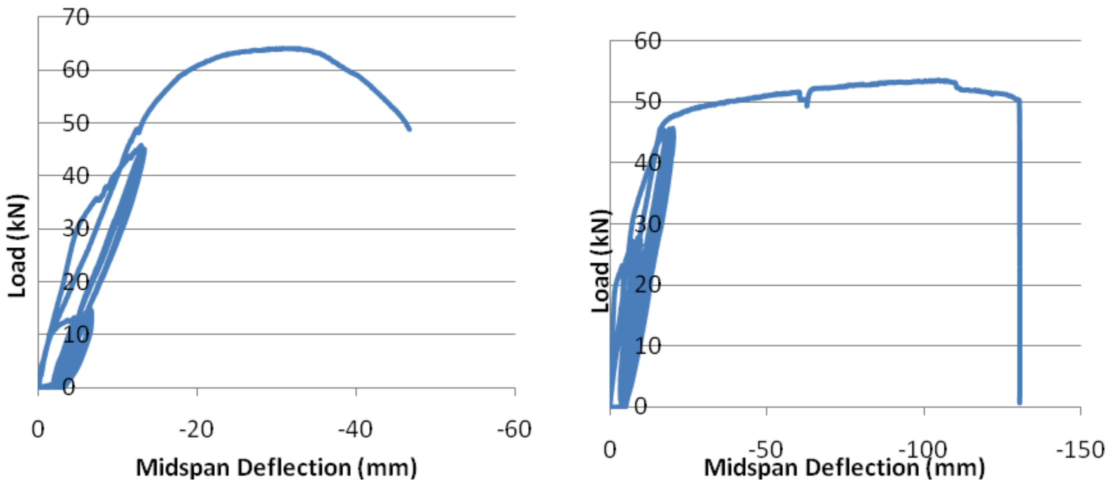
As described in Section 1, the points, $\Delta_1$ and $\Delta_2$ are used to calculate the area under the load-deflection curve to determine $W_0$ and $W_1$ where $W_0$ is the area under the curve between the start of the load deflection plot and $\Delta_1$, and $W_1$ is the area under the curve between $\Delta_1$ and $\Delta_2$. The ratio of $W_1/W_0$ is an indication of a slab's ductility, with a higher ratio corresponding to a more ductile slab. This methodology has been used to assess the ductility parameter of the slabs tested as the data is presented in Table 5. The determination of the work done was based on the final load cycle of the appropriate load-deflection curve. Typical Load-Deflection curves are shown in Figure 8 for the Control 1 and N10 slabs which highlight the contrast between the mesh only slab and the N class bar only slab.

The fibre slabs had larger increases in deflection from yield to collapse when compared to the control slabs. The Fibre One slab had an increase of 51mm, which was equivalent to an increase of 50% on the control slab's average. The Fibre Two slab had an increase of 47mm, equivalent to a 40% larger increase on the control slab's average increase. The ductility ratios of the fibre slabs were approximately twice that of the control slabs suggesting that the addition of steel fibres assisted in producing a more ductile failure when compared to the control slabs, although there was minimal difference in the behaviour of the slabs at the two dosage rates. The fibre slabs had ductility ratios less than that of the mixed reinforcing slab – CS1- which in turn had improved ductility performance in comparison to the control slabs. None of the mesh reinforced slabs had ductility ratios of the order of magnitude of the N class reinforced slabs which were around 19.5±1.5 on average. The slab with two layers of SL72 had a similar ductility ratio to the Control slabs despite the higher percentage elongation observed with the SL 72 mesh tension tests.

Structural members with ductility ratios less than 2 are considered non-ductile; all slabs met this minimum requirement for general design.

**Table 5. Ductility Measure $W_1/W_0$– work absorbed**

| Slab | $\Delta_1$ | $\Delta_2$ | $\Delta_2 - \Delta_1$ | Work (kNmm) | | Ductility Ratio |
|---|---|---|---|---|---|---|
| | | | | $W_0$ | $W_1$ | $W_1/W_0$ |
| Control One | 14 | 47 | 33 | 384 | 1984 | 5 |
| Control Two | 17 | 52 | 36 | 450 | 1983 | 4 |
| Fibre One | 14 | 65 | 52 | 361 | 3176 | 9 |
| Fibre Two | 13 | 60 | 47 | 344 | 2994 | 9 |
| CS1 | 13 | 93 | 80 | 250 | 2789 | 11 |
| CS2 | 13 | 117 | 104 | 245 | 5314 | 21 |
| N10 | 15 | 130 | 115 | 324 | 5782 | 18 |
| SL72 | 14 | 47 | 33 | 388 | 1804 | 5 |



(c) Control 1 (Mesh Only)

(b) N10 (N10 bar only)

**Figure 8. Mid-span Load - Deflection with indicative Δ1 and $\Delta_2$**

## 3. Concluding Comments

The use of steel fibre reinforced concrete in conjunction with Class L reinforcing mesh in the Fibre One and Fibre Two slab specimens resulted in an increase in ductility when compared to the two control slabs (with mesh only). The increase in ductility was evident by the higher ductility ratios and it could be seen from the load deflection responses that the slabs containing steel fibre reinforced concrete exhibited a plateau in the post yield stage of loading. The addition of steel fibre reinforced concrete resulted in a minor increase in their ultimate moment capacities and the deflection of the fibre slabs was greater than the control slabs, suggesting that the inclusion of fibres increases the amount of (deflection) warning prior to failure of slabs.

The use of N class reinforcing bars in conjunction with Class L reinforcing mesh in Slab CS1 slab resulted in an increase in ductility when compared to the two control slabs (with mesh only) for a similar reinforcing ratio. The increase in ductility was evident by the higher ductility ratio and it could be seen from the load deflection response and failure mode; with concrete crushing observable on the compressive face of the slab and the N class bars remaining un-fractured. The addition of N class reinforcing to a lightly mesh reinforced slab resulted in an increases the amount of (deflection) warning prior to failure of slab. Further investigation into the behaviour and design of mixed reinforced slabs may be warranted, however, the ease of placement of the bars needs considerations as tying the N class bar below the mesh bars is not practicable.

## 5. Acknowledgement

The authors acknowledge the technical and practical contribution of Dr Ian Chandler to this research programme. The authors also acknowledge the contribution of Eric Swartz who was also part of the undergraduate team but whose slabs are not presented in this paper.

## 6. References

1. Standards Australia. 2009. "*Concrete Structures*. *AS 3600-2009*", Standards Australia, Sydney.
2. Standards Australia. 2001. "*Steel Reinforcing Materials*. *AS 4671-2001*" Standards Australia, Sydney.
3. Foster, S., A. Kilpatrick. 2008. "The use of low ductility welded wire mesh in the design of suspended reinforced concrete slabs". *Australian Journal of Structural Engineering* 8 (3): 237-248.
4. Gilbert, R., Z. Sakka. 2009. "Strength and ductility of corner supported two-way concrete slabs containing welded wire fabric". *24th Biennial Conference of the Concrete Institute of Australia 2009.*
5. Gilbert, R.I., S.T. Smith. 2003. "Tests on RC slabs reinforced with 500MPa welded wire fabric". *Australian Journal of Civil Engineering.* 1 (1): 59-66.
6. Warner, R.F., B.V. Rangan, A.S. Hall and K.A. Faulkes. 1998. *Concrete Structures*. Melbourne: Addison Wesley Longman Australia
7. Patrick, M and Keith, J (2008) "New Developments in the Testing, Design and Construction of Concrete Structures Incorporating Class L Reinforcing Mesh". Steel Reinforcement Institute of Australia, Sydney NSW Australia, MP Engineers Pty Limited, Melbourne VIC Australia.