Available online at www.uofk.edu
Proceedings Vol. 1 pp. 86-95
Annual Conference of Postgraduate Studies and Scientific Research
17-20 February 2012-10-17 Friendship
Hall, Khartoum

Fibrous Reinforced Concrete Slabs

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Abstract: The paper presents the results of a theoretical and an experimental work performed at the Khartoum University, Civil Engineering Department Structure lab. The work aimed to obtain knowledge concerning the influence of steel fibers on the behaviour of reinforced concrete slabs. A comparative study was conducted theoretically and experimentally. In the experimental work, tests were conducted on six simply supported slabs, which were divided into three groups according to steel fiber contents 0%, 1%, and 2% by volumes, each group contained two slabs, one isotropically reinforced and the other orthotropically reinforced. All slabs were subjected to uniformly distributed load. The deflections were measured using displacement transducers, which were positioned at different locations on the bottom surface of concrete slab. The strains were also measured using strain gages embedded on reinforcement surface at different locations and glued on the top and bottom concrete surface. The failure modes were observed and the load was recorded using load cell. The instruments were connected to TDS303 Data Logger. The performance of the specimens is analyzed and compared with the theoretical investigations using BS 8110 Codes and yield line method based upon calculations of the moment of resistance and load carrying capacity respectively. The deflection, curvature and strain were calculated based on the elastic theory through the area moment theorems and partially cracked section. It was found that the steel fiber content had an influence ranging from little to significant on the tested behaviours of slabs. Good correlation of theoretical and experimental results was clearly noticed when compared to each other.

Keywords: *Steel fibers reinforced slab; Isotropic; Orthotropic; Ultimate load; First crack load; Deflection; Strain.*

1. INTRODUCTION

Steel fibers reinforced concrete (SFRC) is defined as concrete containing randomly oriented discrete steel fibers. When steel fibers are added to a concrete mix, they distributed randomly and act as crack arrestors, changing concrete from a brittle material to a ductile one, in addition to improving the toughness and flexural rigidity [1]. Steel fibers also improve the tensile strength. The main incentive of adding steel fibers to concrete is to improve the properties, strengths, control crack propagation and crack widening after the concrete matrix has cracked [2].
Studies to determine strength properties of SFRC and mortar began in the laboratories of the Portland Cement Association in the late 1950's [3]. During the late 1960's and early 70's, fiber reinforced concrete was studied and tested extensively, and subsequently was in a variety of demonstration projects in the USA [4].
Although the technology has been broadly accepted and the advantages of the SFRC are well recognized, the actual practical usage in Sudan as research studies is still in its early stages and may be nothing in the field works.
The previous researches showed that the greatest number of applications of SFRC has been in the area of slabs and floors, bridge decks, airport pavements, parking areas and cavitations and erosion environments [5] [6]. SFRC show that the material can offer distinct advantages compared to concrete without steel fibers. Slabs are structural applications that could benefit from these advantageous.

2. RESEARCH SIGNIFICANCE

The purpose of this research is to investigate and evaluate the usage of steel fibers in reinforced concrete slabs and to give broader ideas about its behaviour in comparison to that of normal conventional concrete slabs theoretically and experimentally. It was shown that cracking and ultimate load of a reinforced concrete slabs were improved due to steel fibers.

3. Experimental Investigation

The scope of the experimental works covers reinforced concrete slabs with and without steel fibers. The mixtures fabricated using Portland cement, fine and coarse aggregates and water. Hooked ended steel fibers with various contents ranging between 0 to 2 percents by volume are added to manufacture the SFRC mixture. Six slabs (1540mm *1175mm in plan and 80mm depth) divided into two groups according to reinforcements isotropically and orthotropically. Each group contained three slabs according to steel fiber contents SI0, SI1 and SI2 for isotropically reinforced slabs and SO0, SO1 and SO2 for orthotropically reinforced slabs. Slabs are subjected to a curing condition at period of 28 days. Only a semi static loading distributed uniformly is investigated, the load was applied gradually at a low rate.

For the isotropically reinforced slabs, the bars spaced at 100 mm centers both way at the bottom, while for the orthotropically reinforced slabs, the bars spaced at 120 mm centers in short direction and 100 mm in the long direction.
The uniformly distributed load was applied to the slab by a hydraulic jack and then by the conventional system of branching out the concentrated load into two point loads and the two point loads into two point loads and so on up to 16 points as shown in Figure 1.

The specimens are supported by a steel frame that should provide line supports. The supporting frame consists of four beams which were welded together. To avoid concentrations of stresses the reactions are transmitted by steel plates from the support to the slab surface. The boundary conditions allow uplift in the corners.

All tested slabs are considered to be simply supported. The support was modeled in such a way that a roller and hinged were created. This was achieved by weld two unequal angles in adjacent edges, while the other two edges of the slab rested free on the top flange of testing frame to allow rotations in all directions and translation in one direction of the slab but not to roll away as shown in Figure 1.

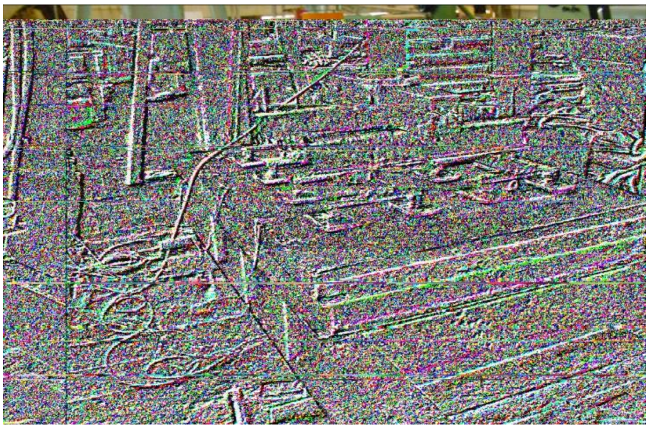


Fig (1). Test setup for simply supported slab

The Measuring devices consisted of electrical resistance strain gages type FLA-10-11 having a gage length of 10mm which were affixed to the certain reinforcing bars in the center of the slab in both directions and adequately protected from direct contact with concrete and water to measure the strain in longitudinal and transverse reinforcement (see Figure 2) and type PL-60-11 having a gage length of 60mm which were glued to the top and bottom of concrete surface after carefully grazing and leveling the surface enough to obtain flat surface to measure the strain in concrete body as shown in Figure 3. Mechanical dial gage TML Displacement Transducers type CDP-5B and CDP-25B were used to measure the deflections at different locations as shown in Figure 4. TML Load Cells type CLP-2MNB was used to measure the applied load. The load increment rate was 30 kN . All the instrumentations were connected to a portable data logger acquisition type TDS-303 as shown in Figure 5.

Fig (2). Typically installed strain gages on the bottom reinforcing bars.

Fig (3). Typically installed strain gages on the top concrete specimens.

Fig (4). Location of deflection measuring points and Strain gauge and at the bottom of slab

Fig (5). Data logger and the instrumentations

4. THEORETICAL INVESTIGATION

The theoretical analysis calculations were performed using BS8110 codes and yield line method. The ultimate capacity is categorized into ultimate moments of resistance using BS8110-1 [7] and ultimate loads which obtained manually by yield line method. The moment of resistance (m) per meter width of section is

$$m = 0.95 f_y A_s (d - 0.45x) \quad (1)$$

The compression depth x is

$$x = \frac{2.346 f_y A_s}{1000 f_{cu}} \quad (2)$$

The first step in any yield line solution is to postulate the yield line pattern. The patterns in general contain unknown dimensions which locate the positions of the yield lines. The ultimate load is found using the principle of virtual work and the equations of equilibrium methods, which gives the same solution [8]. The general case of uniformly loaded simply supported rectangular slabs isotropically or orthotropically reinforced with bars is

$$p = \frac{24 m_x}{\alpha^2 L^2 \left\{\sqrt{\left(3/\mu + \alpha^2/\mu^2\right)} - \alpha/\mu\right\}^2}$$

$$\mu = m_y / m_x \,,\quad \alpha = L_x / L_y \,,\quad L = L_y \quad (3)$$

The elastic analysis theory based on the gross concrete section may be used to obtain moments for calculating deflections. The method for calculating deflation is set out in BS 8110-2 [9]. The method given is to assess curvatures and to use these values to calculate deflections [10].

The curvature at a section can be calculated using assumption set out in BS 8110-2 [9]. The neutral axis depth x of a partially cracked section should be computed by equating the tensile and compressive forces. The strain distribution and the steel and concrete compressive stresses are determined after the moment has been adjusted to allow for the contribution of the concrete tension.

The tension force in concrete equal to $\frac{1}{2}\frac{b(h-x)^2}{d-x} f_{ct}$. BS 8110-2 [9] recommended values for f_{ct} equal $1 N/mm^2$ and $0.55 N/mm^2$ for short and long terms loading respectively. The lever arm of this force about the neutral axis is $\frac{2}{3}(h-x)$, therefore moment due to concrete tension is $\frac{1}{3}\frac{b(h-x)^3}{d-x} f_{ct}$.

The net moment to be resisted by the concrete compression and by the forces in the reinforcement is

$$M = M_{ap} - \frac{1}{3}\frac{b(h-x)^3}{d-x} f_{ct} \quad (4)$$

Moment area theorems are used to express slopes and deflections in terms of the properties of the $\frac{M}{EI}$ diagram. The moment of inertia is to be calculated as follows:

$$I_x = \tfrac{1}{3} b x^3 + \alpha_e A_s (d-x)^2 + \alpha_e A'_s (x - d')^2 \quad (5)$$

where α_e is the modular ratio, $\alpha_e = E_s / E_c$. For elastic members, the quantity $\frac{M}{EI}$ is equal to the curvature $\frac{1}{r}$ [11].

The strain in reinforcing steel at the tension zone and concrete at the compression zone are given by Equation 6 and 7 respectively

$$\varepsilon_s = (d-x)\frac{1}{r} \quad (6)$$

$$\varepsilon_c = x\frac{1}{r} \quad (7)$$

where EI is the flexural rigidity of slab, ε_s is strain in reinforcing steel, is strain in concrete, d is effective depth of slab, x depth to the neutral axis

Useful geometrical properties for a parabola are used in term of moment area theorems with uniform load as for simply supported case. The centre deflection is [10]

$$\omega = \tfrac{2}{3}\frac{M}{EI}\frac{l}{2}\frac{5}{8}\frac{l}{2} = \tfrac{5}{48}l^2\frac{M}{EI} = Kl^2\frac{1}{r}$$

$$K = 5/48 = 0.104 \qquad (8)$$

5. EXPERIMENTAL RESULTS AND DISCUSSION

The loads for slabs with steel fibers were always greater than the corresponding values for slabs without steel fibers, while the deflections and strains in reinforcements were always smaller than the corresponding values. The decrease in deflections and strains might be due to the increase in the flexural rigidity and ductility, see Table 1 through Table 3 and Figure 6 through Figure 8.
Slabs (SI1 and SO1) which used the 1% of steel fibers exhibited an improvement in the both first cracking and failure loads compared to the control slabs. After first cracking load was reached, all slabs were still intact but the slabs failed when the failure load was reached. For these slabs the first cracking loads were 7.8 % and 6.7 % higher than the control slabs (SI0 and SO0) respectively, while the failure loads are 16.1% and 11.9% higher respectively.
Also slabs (SI2 and SO2) which used the 2% of steel fibers recorded a substantial increase in the both first cracking loads compared to the control slabs by 10% and 12.7% respectively, while the failure loads increase by 40.4% and 45.6% respectively. The percentages appeared that compared to the control slabs, the increase of first cracking loads were very small as compared with the increase in failure loads.

Table (1). Effect of steel fibers on load capacity

Slab type	Experimental load in kN		Yield Line and BS8110-1 load in kN
	First crack	Failure	Failure
SI0	221.7	315.3	343.64
SI1	239	366	346.29
SI2	243.3	442.6	347.18
SO0	209.6	290.5	320.69
SO1	223.7	325	322.97
SO2	236.3	422.8	323.74

Similarly, the deflections at the centre of slabs at the failure load were also decreased by 11.25% and 8.82%, respectively for slabs used 1% of steel fibers and 14.38% and 15.9% respectively for slabs used 2% of steel fibers.

Table (2). Effect of steel fibers on deflection at the centre

Slab type	Experimental deflections in *mm*		BS8110-2 deflections in *mm*
	At first crack load	At failure load	At failure load
SI0	8.2	16	14.67
SI1	7.5	14.2	14.56
SI2	7.1	13.7	14.51
SO0	9.4	17	13.43
SO1	8.5	15.5	13.29
SO2	7.3	14.3	13.23

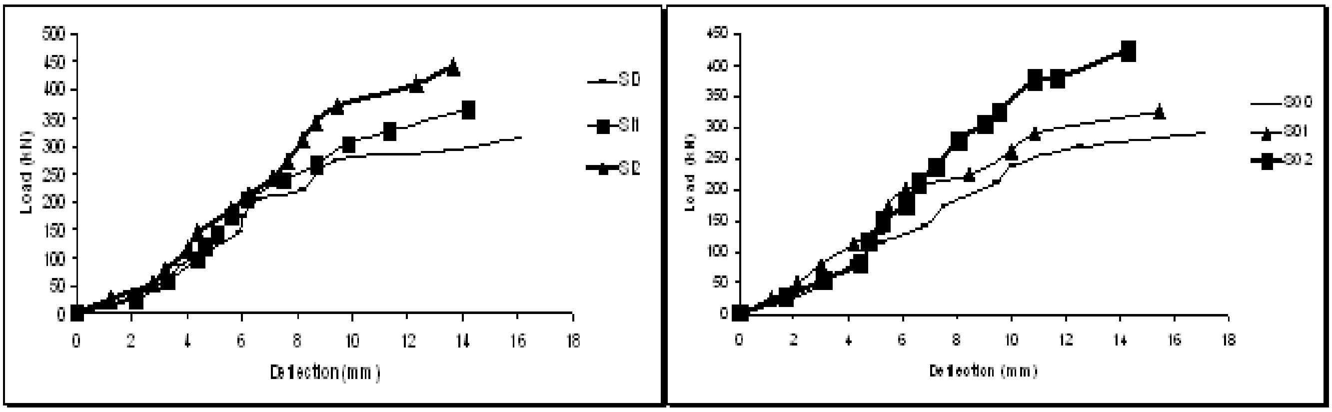
The strain gages readings for reinforcement indicate a decrease in strain at the first cracking load and failure load as the volume percentages of steel fibers is increased. This is explained by the fact that part of the load applied is transferred to the steel fibers. The slabs which used the 1% and 2% of steel fibers recorded obvious reduction in strain compared to the control slabs by percentages.

The strain gages readings for concrete indicate a decrease in strain before the first cracking load reached but at the first cracking load the strain was increased until the failure load was reached as the volume percentages of steel fibers is increased. This is explained by the fact that fibers concrete surface is more ductile than the plain concrete.

Table 3 Effect of steel fibers on strains in steel reinforcement ($*10^{-3}$)

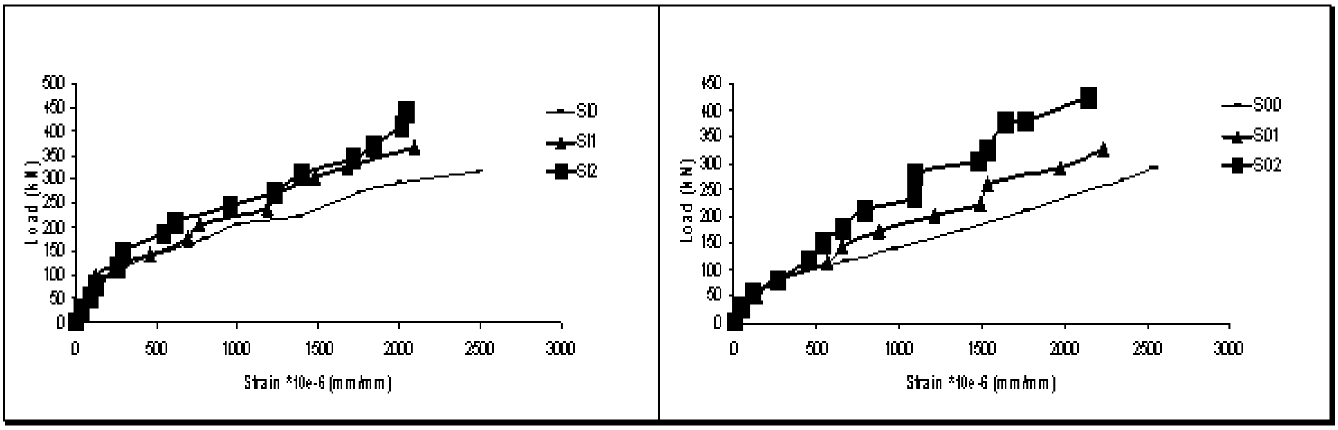
Slab type	Experimental strain at						BS8110-2 strain at
	first crack load			failure load			failure load
	ε_1	ε_2	ε_3	ε_1	ε_2	ε_3	ε_1
SI0	1.3838	0.6947	0.8657	2.495	1.321	1.634	2.547
SI1	1.1856	0.8767	1.0365	2.095	1.582	1.9021	2.579
SI2	0.9547	0.8974	1.0726	2.045	1.8096	2.0198	2.587
SO0	1.765	0.701	1.095	2.542	1.503	1.894	2.472
SO1	1.588	1.308	1.321	2.2352	1.801	1.9878	2.484
SO2	1.0905	1.3212	1.522	2.141	1.901	2.1567	2.486

ε_1**:** Steel strain at mid short span**,** ε_2**:** Centre top strain concrete**,** ε_3**:** Centre bottom strain concrete



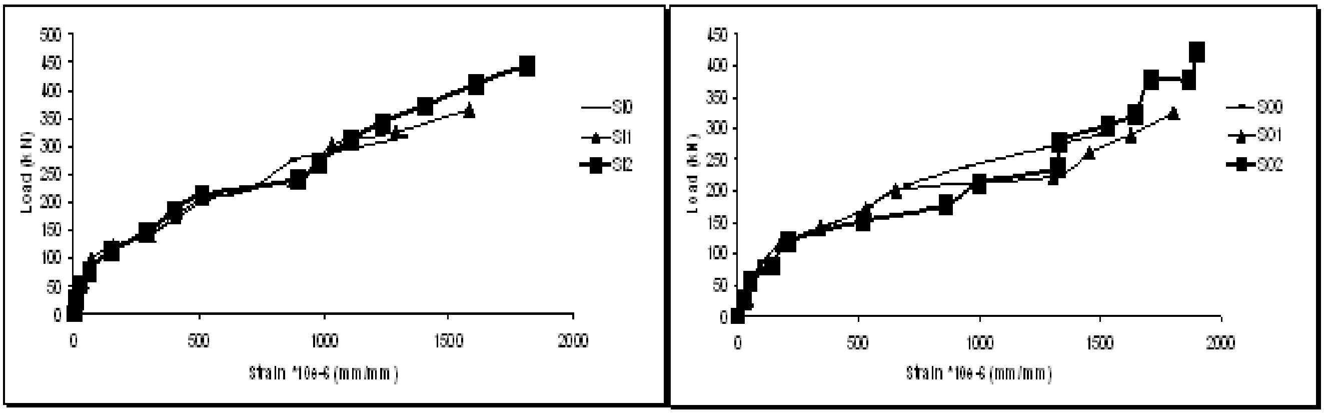
(a) (b)

Fig (6). Failure load versus deflection curves at mid-span for slabs (a) SIs (b) SOs



(a) (b)

Fig (7). Load versus steel strain curves at mid short span for slabs (a) SIs (b) SOs



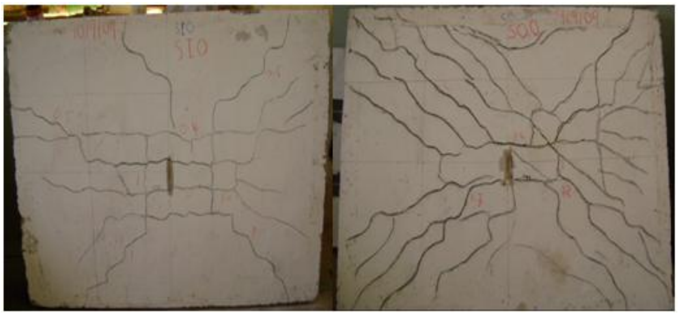
(a) (b)

Fig (8). Load versus top strain curves in concrete at centre of slabs (a) SIs (b) SOs

Flexural first cracks formed and appeared on the bottom surface mid centre regions of concrete slabs closest to the four interior load points of the diagonal lines that extends from the centre to corners. Theses cracks formed were short and increased slightly as the load increased running almost to the corners, followed by a smaller crack on each side. The slab became unstable when the severe cracks appear clearly. For all slabs under uniformly distributed loads, the experimental crack patterns were identical to the predicted ones by the assumptions of the yield line theory as shown in Figure 9 through Figure 11. However, for the slabs with steel fibers, the experimental crack patterns were slightly different from the predicted ones.

Test results showed that all slabs failed in flexural as expected with increase in first crack load and load carrying capacity for the slabs containing 1% and 2% by volume of steel fibers, no shear failure was observed.

The control slabs exhibited a conventional ductile flexural mode of failure by which the slabs failed by yielding of steel reinforcement followed by crushing of concrete. All other specimens failed by yielding of steel reinforcement with cracking of concrete which was preceded by large strains of bottom concrete surface. Crack patterns were marked on the slabs at every load intervals. The crack pattern did demonstrate that steel fibers play an important role in delaying the occurrence of cracks reducing the distribution of cracks in slabs. This effect, therefore, greatly enhances both serviceability and durability of slabs.



(a) **(b)**

Fig (9). Slab (a) SI0 and (b) SO0 after failure

(a) **(b)**

Fig (10). Slab (a) SI1 and (b) SO1 after failure

(a) **(b)**

Fig (11). Slab (a) SI2 and (b) SO2 after failure

6. COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS

The comparison of the predictions using the theoretical model developed in this study and the experimental results from the testing described above are presented. It shows that the predictions are in a good agreement with the experimental results for slabs

The computed ultimate loads using yield line methods are given in Table 1 and are compared with the maximum loads measured experimentally which appeared in the same table. It was found that the actual measured values of failure loads were greater than the calculated ones. The difference was small for the slabs without steel fibers. The theoretical calculations revealed that as the volume percentage of steel fibers increases the ultimate load is also increased.

For the slabs without steel fibers, the experimental failure load were identical to the theoretical ones while for slabs with steel fibers, the experimental failure load were higher than the theoretical ones.

Slab SI0 was loaded until a load of 315.3 kN which was lower by 28.34 kN of the predicted load determined by yield line method. The ratio of measured failure load to that predicted by yield line method was 8.99% for SI0 slab, while for SO0 slab was 10.39%. For SI1 and SI2 slabs the ratios were -5.38% and -21.56% respectively, while for SO1 and SO2 the values were -0.62% and -23.43% respectively.

The ultimate load predicted by yield line methods of slabs with steel fibers was always less when compared with the experimental results because the assumptions did not include the strong effect of steel fibers on the tensile strength or the modulus of rupture of concrete.

The results of computed using BS8110-2 and measured deflections corresponding to the maximum load are listed in Table 2. There was reliable and reasonable agreement between the theoretical and experimental results.

The ratio of measured deflection at failure load to that predicted by BS8110-2 at the centre of slabs was -8.31% for SI0 slab, while for SO0 slab was 21.00%. For SI1 and SI2 slabs the ratios were 2.33% and 5.91% respectively, while for SO1 and SO2 the values were -14.25% and -7.48% respectively.

Figures 12 and Figure 13 show the load-deflection curves of slabs obtained theoretically and experimentally. It is observed that the curves show a great matching up to about 30 percent of load as shown in the figures.

Deflections for reinforced slabs with steel fibers were always less than the corresponding values for reinforced slabs without steel fibers obtained from experimental and theoretical investigations as shown in Table 2. The decrease in deflection might be due to the increase of the strengths and ductility of concrete which resulted in an increase of the flexural rigidity of the slabs. Also deflections for orthotropically reinforced slabs were always greater than the corresponding values for iostropically reinforced slabs obtained from experimental and theoretical investigations. The increase in deflection might be due to the reduction of the amount of reinforcement which resulted in a reduction of the flexural rigidity of the slabs. In general, the load–deflection curves for all slabs given by theoretical calculations agreed quite well with the experimental results as shown Figure 12 and Figure 13 and Table 2

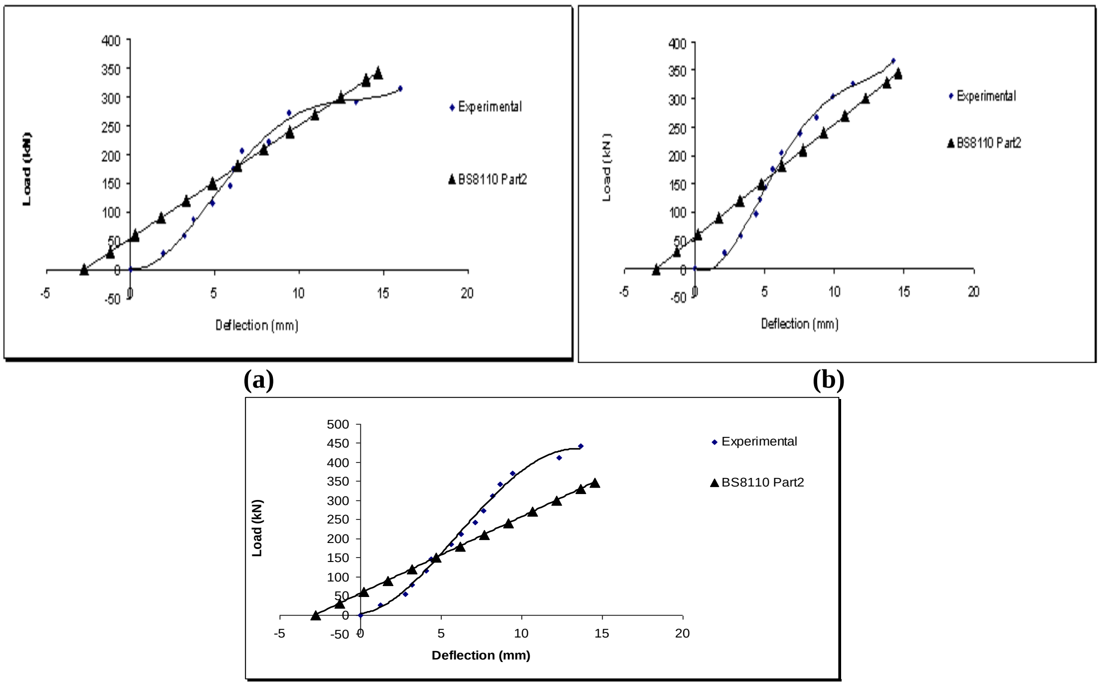


Fig (12). Load-deflection curves for (a) SO0 (b) SO1 and (c) SO2 slabs

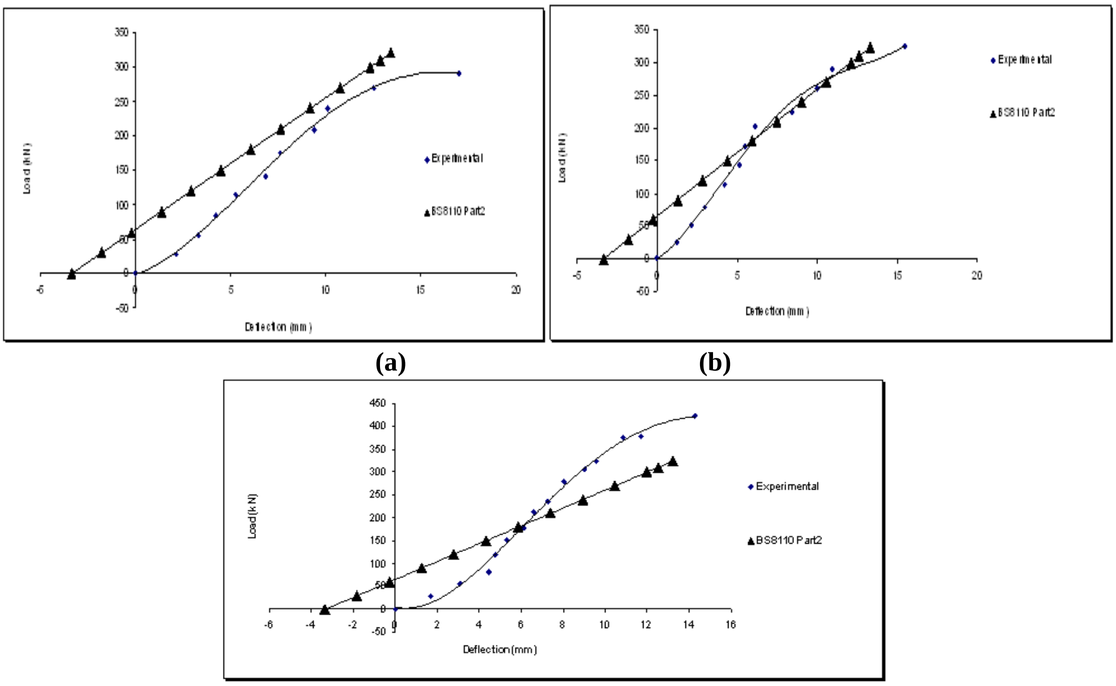
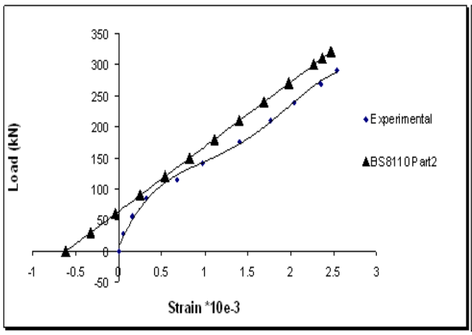
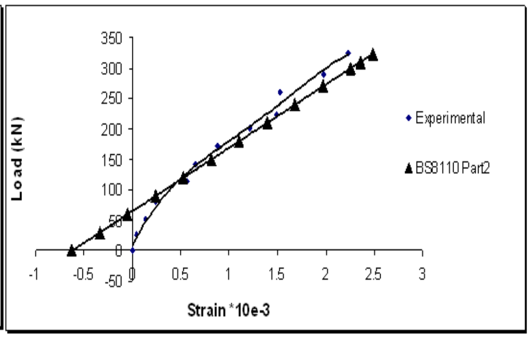


Fig (13). Load-deflection curves for (a) SI0 (b) SI1 and (c) SI2 slabs

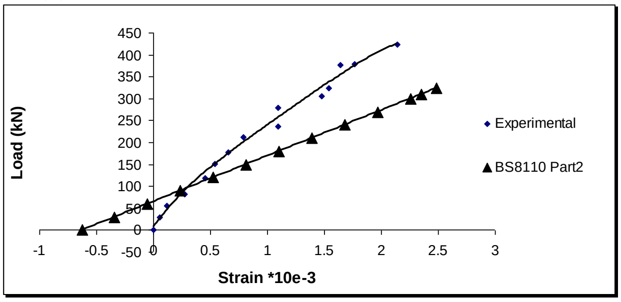
The results of strains implemented by BS8110-2 showed a good agreement compared with experimental results. The values of strains shown in Table 3 indicating that the reinforcement has reached the yield strain at ultimate conditions which confirmed the theoretical assumptions. Comparisons of the load-tensile strain plots from the theoretical calculations with the experimental strain readings for the main steel reinforcing at mid-span for each slab are shown in Figures 14 and Figure 15. From those figures, the trend of theoretical calculations, experimental results were similar. Strain value results by BS8110-2 were lower than the experimental slabs at the same load. The reversing strain in the experiments was possible due to a local effect caused by the major cracks. This behaviour did not occur in theoretical calculations and models. In general, the plots of load versus strains in the main steel reinforcing from the theoretical calculations had similar trends to those from the experimental results. In the lower ranges of loading, the strains calculated theoretically were nearly the same as those measured in the actual slabs. However, after that, an inconsistency occurred in the results data. For all slabs, theoretical calculations predicted that the stains occurring in the steel were lower than those in the actual slabs.



(a)

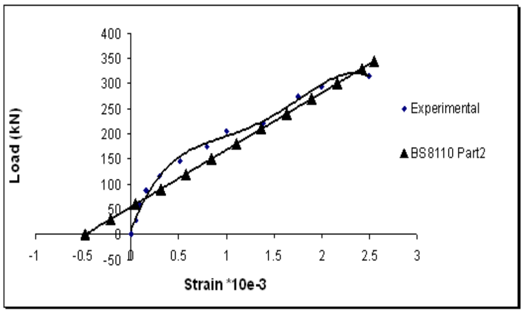


(b)

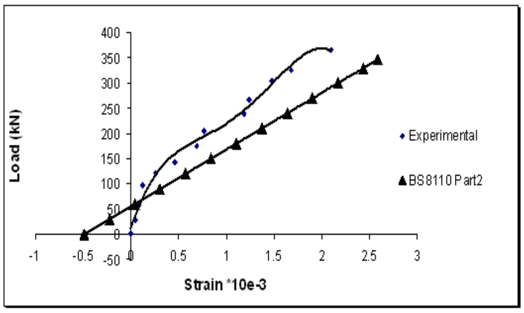


(c)

Fig (14). Load-strain curves for (a) SO0 (b) SO1 and (c) SO2 slabs



(a)



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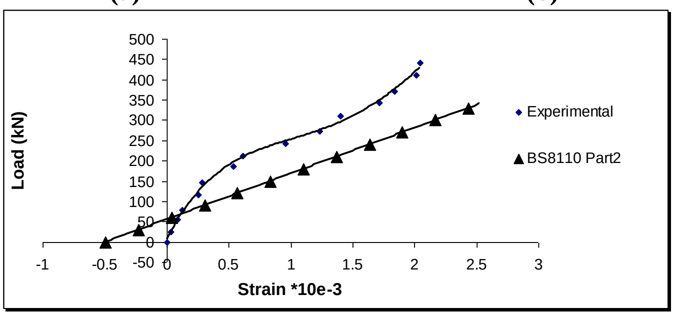

(c)

Fig (15). Load-strain curves for (a) SI0 (b) SI1 and (c) SI2 slabs

The stiffness of the cracked concrete elements in the theoretical models reduces to zero, so they cannot resist tension. Therefore, the tensile strain in the steel does not vary as in the actual slab but its constant across the element. For this reason, strains from the theoretical calculations could be different compared with experimental ones. Also the inconsistency in the strain of the slabs between the models and experimental results could be due to cracks in close proximity to the strain gage. A crack could create additional tensile strains. For the slab with steel fibers, the composite would provide some constraint of the crack and therefore, less strain in the immediate vicinity of the crack

7. CONCLUSIONS

The observations and results from the slabs test presented herein lead to the following concluding remarks:-

- The test results showed that the ultimate deflection has remarkable decreased when steel fibers were added into the concrete slabs. Moreover slabs including *2%* steel fiber have lower ultimate deflection than the concrete slab that included *1%* steel fibers. Also Deflection profiles of *1%* steel fibers reinforced concrete slabs showed a significant decrease of its values at the same level of loads compared to control slabs. The effect is even more prominent if *2%* steel fibers content is used at the same time as well.
- Addition of steel fibers with contents of 1% and 2% to the concrete mix significantly enhances the first crack and failure loads relative to plain concrete and the most rapid increase occurred at 2% steel fibers.
- The slabs which used the *1%* and *2%* of steel fibers recorded obvious reduction in strain compared to the control slabs. This is explained by the fact that part of the load applied is transferred to the steel fibers
- Failure of slabs with steel fibers exhibited a conventional ductile flexural mode in which the control slabs failed by yielding of steel reinforcement followed by crushing of concrete.
- Decreasing the reinforcement amount of orthotropically reinforced slabs did result in reductions in maximum loads and increases in the deflections. .
- The crack pattern did demonstrate that steel fibers play an important role in delaying the occurrence of cracks and reducing the distribution of cracks in slabs. The crack width was also decreased when adding steel fibers.
- Bonding between concrete and reinforcement was improved by using steel fibers. This resulted in an enhancement of the tension stiffening and appeared from occurrence of cracks.
- The slabs without steel fibers unloaded rapidly before becoming unstable, while the slabs containing steel fibers unloaded gradually and even turned to tension before it became unstable, which suggested that the slabs containing steel fibers continued to redistribute the stresses while cracking propagated upward

NOTATION

f =	stress at any strain ε
f'_c =	cylinder compressive strength
ε_0 =	ultimate strain
d_s =	fiber diameter
v_s =	volume percentage of fibers
L_x, L_y =	Slab dimension
d =	Effective depth of slab
f_{cu} =	cube compressive strength
f_y =	Yield strength of steel
E_c =	modulus of elasticity of concrete
l_s =	fiber length
E_s =	modulus of elasticity of steel
A_s, A'_s	Area of reinforcement at the bottom and top
m_x, m_y	moment of resistance per meter width in x and y directions

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