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Effect of Glass Fibre Reinforced Polymer Reinforcements on the Flexural Strength of Concrete One Way Slabs under Static and Repeated Loadings

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Abstract: The purpose of this experimental study is to investigate the flexural behaviour of concrete one way slabs reinforced with Glass Fibre Reinforced Polymer (GFRP) reinforcements as well as conventional (Steel) reinforcements when subjected to static and repeated loadings. A total number of forty slabs of size 2.4×0.6 m were cast, out of which twelve slabs were reinforced with steel reinforcements and the remaining slabs were reinforced with GFRP reinforcements. Twenty numbers of slabs were tested under static loading condition and another twenty numbers of slabs were tested under repeated loading condition. Various parameters like types of reinforcements, longitudinal reinforcement ratio, grade of concrete and thickness of slabs were used in the construction of slabs and the results were analyzed. This research had been restricted with the observation of number of load cycles applied to the slab specimen up to failure, deflection characteristics, crack width and number of cracks developed. From the fatigue results, S-N curve was drawn. It was observed that the fatigue response of sand coated GFRP reinforced slabs is superior to all the other types of slabs.

Key words: Glass fibre reinforced polymer reinforcements, conventional reinforcements, one way slabs, flexural behaviour, static loading, repeated loading

INTRODUCTION

Corrosion of steel is one of the major parameters which weakens the structures. The replacement of conventional steel reinforcement with FRP reinforcements has been investigated to overcome the corrosion problem due to their excellent properties like corrosion resistance, high tensile strength and good non magnetization properties. Fatigue problems may arise in concrete structures which are constantly and continuously subjected to repeated loadings. Generally, concrete engineering structures such as bridges, pavements and offshore structures are subjected to repetitive fatigue loadings. Several experimental studies have been performed regarding the behavior of concrete structures reinforced with FRP bars (ACI Commiltee 440 R, 1996; Katz, 2000). EI-Ragby *et al*. (2007) tested six full-size bridge deck prototypes of length 3000 mm, 2500 mm width and 200 mm thick which were reinforced with five GFRP bars and one conventional steel bar using different reinforcement ratios under both constant fatigue loading and accelerated fatigue loading with variable amplitude and investigated that GFRP reinforced slabs had the lowest residual deflection, greatest stiffness and a longer fatigue life about three times than the steel reinforced slabs. The flexural response of concrete beams reinforced with FRP reinforcing bars and bond strength of FRP reinforcing bars in concrete were studied by Benmokrane *et al*. (1995, 1996). Michaluk *et al*. (1998) carried out experiments on eight one-way concrete slabs under static loading conditions and examined their behavior prior to cracking, cracking, ultimate capacities and modes of failure. Accordingly, some design recommendations and guidelines

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are also provided. Ganesh Thiagarajan (2003) reported the results of an experimental and analytical comparison on the flexural behaviour of concrete beams reinforced with sand blasted carbon fibre based composite rods. Kae-Hwan Kwak and Jong-Gun Park (2001) studied the damage mechanism due to shear fatigue behavior of FRP reinforced concrete slabs under repeated loading. The relationship between number of cycles and deflection, crack growth and modes of failure with the increase of number of cycles, fatigue strength and S-N curve were observed. Theriault and Benmokrane (1998) presented the test results of 12 concrete beams reinforced with FRP rods. The main parameters investigated in this study include the reinforcement ratio and the concrete strength. Theoretical models are proposed for the prediction of crack width, crack spacing, load deflection response, ultimate capacity and modes of failure. Ombres *et al*. (2000) made an experimental investigation on the flexural behaviour of GFRP reinforced one way slabs. Rashid *et al*. (2005) tested ten high strength concrete beams reinforced with Aramid Fibre Reinforced Polymer (AFRP) bars and discussed the major critical issues in the flexural design. The bond strength of GFRP bars under fatigue and in normal strength concrete were studied by Adimi *et al*. (2000) and Roman and Robert (2005), respectively.

The present study explicates the investigations of the flexural behaviour of a total number of forty one-way slabs reinforced with three types of GFRP reinforcements and conventional reinforcements under both static and repeated loadings. Out of forty slabs, twenty number of slabs were tested under static loading and the remaining twenty number of slabs were tested under repeated loadings. From the static test, the ultimate load carrying capacities, the deflection for each and every equal increment of loadings and corresponding crack widths of the slabs were observed. From the conducted fatigue test, the relationship between number of load cycles and deflection, the development of crack widths with the number of load cycles were observed. Two thicknesses (100 and 120 mm), two grades of concrete (M_{20} and M_{30}), four types of reinforcements (Grooved GFRP, Sand coated GFRP, Plain GFRP and Conventional) and two types of reinforcement ratios provided in longitudinal direction i.e., increasing the number of longitudinal bars (0.82 and 1.15%) were considered as variables in this investigation.

MATERIALS AND METHODS

The entire slab specimens were cast using normal weight concrete with two different grades of concrete i.e., 20 and 30 MPa. After casting, the specimens were allowed to cure for about 28 days which helps the concrete to stabilize its own properties like compressive strength and modulus of elasticity. Ordinary Portland cement with a specific gravity of 3.15 was used for the concrete mix. The maximum size of the coarse aggregate was 20 mm with a specific gravity of 2.8. The specific gravity of the fine aggregate was 2.6. The mix proportions of the normal weight concrete were shown in Table 1. The compressive strength of standard cubes which were cast using the above tabulated proportions were observed as 28 and 39 N mm^{-2} for M_{20} and M_{30} grade of concrete and were slightly greater than the target mean strength.

In this study, slabs were reinforced with grooved, sand coated, plain GFRP reinforcements and Fe415 reinforcements. GFRP reinforcements were manufactured by pultrusion of S-glass continuous fibres and thermosetting polyester resin. To enhance the bond characteristics the surface of GFRP reinforcements were wrapped by helically glass fibre strands (grooved GFRP) and Sand coatings (sand coated GFRP). Table 2 shows the mechanical properties of the reinforcements. The basic properties

Table 1: Properties of concrete

Material	M_{20} grade of concrete	M_{30} grade of concrete
Cement	62 kg	77.00 kg
Fine aggregate	80 kg	84.70 kg
Coarse aggregate	183 kg	204.82 kg
Water	28 L	31.00 L

Table 2: Properties of reinforcements

S. No.	Specification of reinforcements	f (MPa)	E (GPa)	d (mm)	Strain (ε)
1	G1	550	60	10	0.006
2	G2	690	88	10	0.005
3	G3	425	40	10	0.008
4	S	415	200	10	0.002

f = Tensile strength of reinforcements, E = Modulus of elasticity of reinforcements, d = Diameter of reinforcements, ε = Strain of reinforcements at ultimate load = f/E

of the concrete and reinforcements were studied in the Structural Engineering Laboratory of Annamalai University by the researchers as Seenivasan *et al*. (2005), Sharon *et al*. (2005) and Sivagamasundari and Kumaran (2007).

EXPERIMENTAL PROGRAM

Experimental Set up for Static Loading Condition

The slabs were kept on the loading frame and were tested under two point loading with simply supported conditions. The slabs were instrumented with a linear variable differential transformer (LVDT of range 0-100 mm) at mid span located at the centre of the slab to monitor deflection. Two LVDTs of range 0-75 mm were used to monitor deflections at right and left loading points of the slab. The load was applied using a 50 tonnes capacity hydraulic jack and a proving ring. Demec gauge (Demouldable mechanical gauge) pellets were pasted at the topmost compression axis, at the middle axis and at the level of reinforcements of slabs to note down the concrete surface strains. The load was given in increments of 2 kN at each stage of loading. The deflections were measured using LVDT, crack widths were measured using crack detection microscope and strains were measured using demec gauge. Fig. 1 shows the experimental test set up. The results of static test of slabs and designation of the slab is shown in Table 3.

Experimental Set up for Repeated Fatigue Loading Condition

All slabs were tested under two point loading with simply supported conditions. A 20 mm thick neoprene sheet was used between the steel plate and the concrete surface to avoid stress concentration. A clear span of 2200 mm was adopted between the supports. A 10 kN capacity with 250 mm stroke cyclic load tester monitored by computer was used to apply the cyclic loads. Demec gauge was used to note down the strains. The slabs were subjected to sinusoidal waveform of fatigue load cycles between a minimum and maximum load levels at a constant frequency 4 Hz. The minimum load level P_{min} was fixed as 10% of ultimate static load of the slab designated as $m_2g_1p_1D_1$ to prevent any impact due to repeated loading and also to represent the superimposed loads on a bridge (Masoud *et al*., 2001). The maximum load P_{max} was fixed as 80% of ultimate static load of the same slab to simulate some kind of overloading on the specimen to enable the failure of the slab within a reasonable time. For the slabs reinforced with plain GFRP reinforcements (which were designated as $m_2g_3\rho_1D_1$, $m_2g_3\rho_2D_1$, $m_3g_3\rho_1D_1$ and $m_2g_3\rho_2D_1$), the minimum and maximum loads were fixed as 10 and 80% of the ultimate static load of slab $m_2g_3\rho_1D_1$, respectively, because of the less ultimate load carrying capacities of plain GFRP reinforced slabs. Before applying repeated fatigue loading, the slabs were pre cracked by applying smaller magnitude of static loading to note down the first crack load and initial propagation of cracks. Figure 2 shows the pattern (sinusoidal wave form) of repeated loading applied on the slabs. The experimental setup for the fatigue loading is shown in Fig. 3. The experimental results of repeated fatigue loading is shown in Table 4. The degree of fatigue damage can be evaluated by the magnitudes of strains in reinforcement, crack width, elastic deflection and residual (plastic) deflection. The magnitude of residual deflections is the energy dissipation of the slab which is considered as a proper measure to estimate the degree of damage. The deflections, crack widths, crack propagation, crack

Fig. 1: Experimental set up for static loading

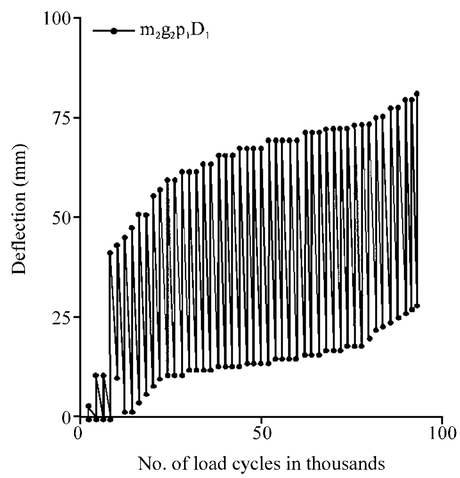

Fig. 2: Sinusoidal wave form of constant amplitude fatigue loading applied on the slab reinforced with sand coated GFRP reinforcements

Fig. 3: Experimental setup for repeated fatigue loading

Table 3: Experimental and theoretical results of one way slabs under Static loading

S. No.	Specification of the slab specimens	Theoretical P_{cr}	Theoretical P_u	Experimental P_{cr}	Experimental P_u	δ_{theo}	δ_{exp}	$w_{cr(mono)}$
1	$m_2g_1\rho_1D_1$	11.4	33.0	11.5	40.0	67.8	70.2	1.70
2	$m_2g_1\rho_2D_1$	12.0	44.0	12.8	51.0	68.0	71.3	1.20
3	$m_3g_1\rho_1D_1$	10.5	38.0	11.0	49.6	66.6	69.5	1.00
4	$m_3g_1\rho_2D_1$	11.1	48.5	12.0	57.5	67.0	70.0	1.00
5	$m_2g_2\rho_1D_1$	11.4	43.6	12.0	55.2	61.0	59.2	0.90
6	$m_2g_2\rho_2D_1$	11.6	56.2	12.4	65.4	62.4	60.4	0.80
7	$m_3g_2\rho_1D_1$	11.6	49.2	12.8	73.5	56.5	60.0	0.80
8	$m_3g_2\rho_2D_1$	12.0	60.4	12.9	82.4	57.0	60.2	0.70
9	$m_2g_3\rho_1D_1$	11.4	28.6	12.1	30.2	70.6	90.0	2.00
10	$m_2g_3\rho_2D_1$	11.8	34.8	12.8	37.4	71.9	87.5	1.80
11	$m_3g_3\rho_1D_1$	13.0	33.6	13.5	36.7	69.5	85.0	1.70
12	$m_3g_3\rho_2D_1$	14.0	40.4	14.0	45.6	68.2	80.2	1.50
13	$m_2S\rho_1D_1$	11.0	30.4	11.5	40.0	25.8	46.0	0.80
14	$m_2S\rho_2D_1$	11.2	38.8	11.9	52.6	26.0	48.0	0.70
15	$m_3S\rho_1D_1$	12.2	32.6	12.7	50.6	24.7	42.4	0.66
16	$m_3S\rho_2D_1$	12.4	40.4	13.0	58.4	25.0	40.0	0.60
17	$m_2g_1\rho_1D_2$	16.0	41.3	17.5	75.6	65.2	60.2	0.50
18	$m_2g_1\rho_2D_2$	16.4	57.0	17.8	92.6	66.7	60.0	0.52
19	$m_2S\rho_1D_2$	16.0	40.0	18.0	62.4	20.0	25.6	0.42
20	$m_2S\rho_2D_2$	16.7	47.0	18.4	90.2	21.2	26.0	0.40

m_2 m_3 = Grades of concrete M_{20}, M_{30} respectively, g_1,g_2,g_3, S=Grooved, Sand coated, plain GFRP and Steel reinforcements, ρ_1 and ρ_2 = Different longitudinal reinforcement ratios 0.82 and 1.15%, respectively; D_1 and D_2 = Effective depth of slab, Designation of the slab $m_2g_1\rho_1D_1$: m_2 = Grade of concrete is M_{20}, g_1 = Grooved GFRP reinforcement, ρ_1 = Longitudinal reinforcement ratio is 0.82%, D_1 = Depth of slab is 100 mm

Table 4: Repeated Fatigue test results of the slabs

S. No.	Designation of slabs	P_u (kN)	Q*	No. of load cycles	$w_{cr(fati)}$ (mm)	Residual deflection (mm)
1	$m_2g_1\rho_1D_1$	40.0	0.80	65,120	1.80	52.0
2	$m_2g_1\rho_2D_1$	51.0	0.63	85,000	1.78	54.0
3	$m_3g_1\rho_1D_1$	49.6	0.65	80,240	1.60	45.4
4	$m_3g_1\rho_2D_1$	57.5	0.56	95,606	1.50	43.6
5	$m_2g_2\rho_1D_1$	55.2	0.58	93,265	1.20	42.6
6	$m_2g_2\rho_2D_1$	65.4	0.49	1,50,010	1.00	40.0
7	$m_3g_2\rho_1D_1$	73.5	0.44	1,25,261	0.80	35.6
8	$m_3g_2\rho_2D_1$	82.4	0.40	2,00,612	0.70	30.2
9	$m_2g_3\rho_1D_1$	30.2	0.80	28,070	2.40	78.2
10	$m_2g_3\rho_2D_1$	37.4	0.64	31,212	2.60	76.0
11	$m_3g_3\rho_1D_1$	36.7	0.65	33,100	2.20	68.2
12	$m_3g_3\rho_2D_1$	45.6	0.53	35,260	2.00	65.0
13	$m_2S\rho_1D_1$	40.0	0.80	67,510	0.70	35.2
14	$m_2S\rho_2D_1$	52.6	0.61	75,222	0.64	32.6
15	$m_3S\rho_1D_1$	50.6	0.63	80,130	0.60	28.6
16	$m_3S\rho_2D_1$	58.4	0.55	92,826	0.56	26.0
17	$m_2g_1\rho_1D_2$	75.6	0.42	3,46,000	0.96	42.8
18	$m_2g_1\rho_2D_2$	92.6	0.35	3,89,220	0.90	40.6
19	$m_2S\rho_1D_2$	62.4	0.51	3,19,352	0.40	20.0
20	$m_2S\rho_2D_2$	90.2	0.35	3,55,818	0.32	16.4

Q* = The ratio of maximum repeated loading (P_{max}) and the maximum static ultimate loading (P_u)

patterns, modes of failure and number of cycles up to failure are measured during the repeated loading at the end of each repeated loading step. Figure 4 and 5 show the residual deflection of slabs versus number of cycles due to constant repetitive loading. From the experiment, it was observed that the residual deflections of GFRP slabs were greater than the conventional slabs. Among the GFRP slabs, sand coated GFRP slabs experienced a large number of cycles and lesser deflections.

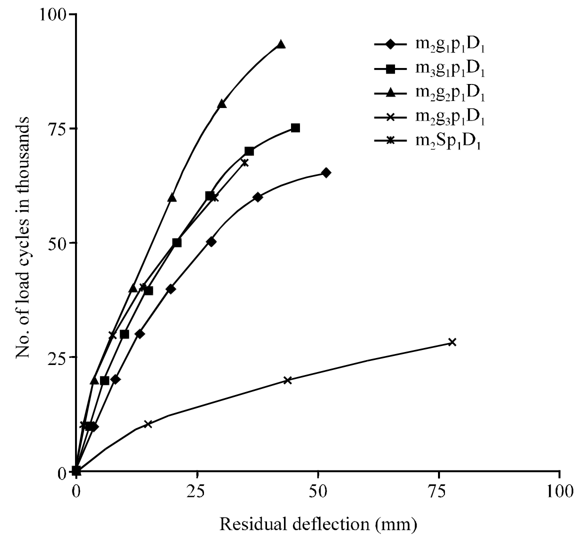

Fig. 4: Residual deflection vs number of cycles of slabs under constant amplitude repeated loading

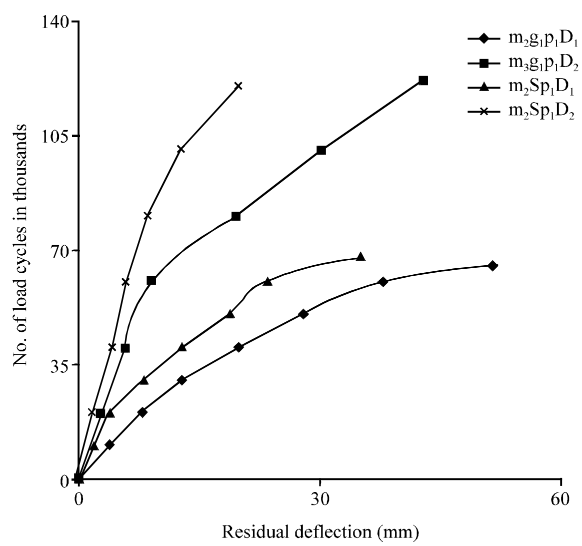

Fig. 5: Residual deflection vs number of cycles of slabs under constant amplitude repeated loading

RESULTS AND DISCUSSION

Test Results under Static Loading

Figure 6-8 show the experimental results of slabs under static loading. From the experimental results, it was observed that the load-deflection response of GFRP reinforced slabs was linear up to the first crack. After the first crack, there was a sudden increase in deflection due to the stiffness reduction of slabs. In case of steel slabs the first crack was initiated at mid span and was accompanied by smaller deflections and crack widths when compared to the GFRP reinforced slabs

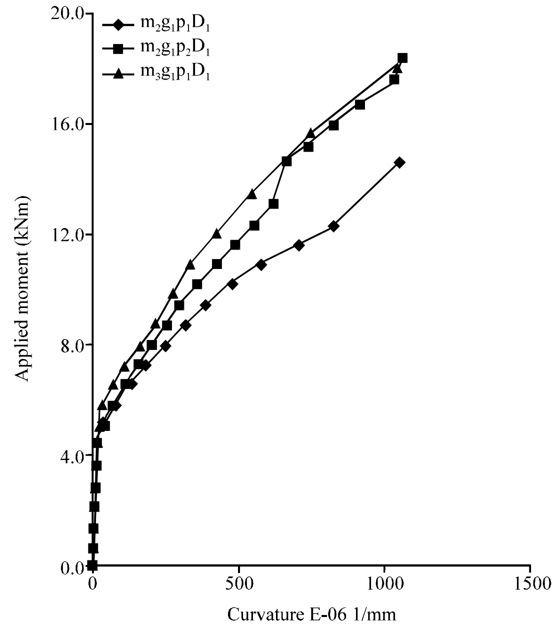

Fig. 6: Effect of concrete grade and reinforcement ratio on moment and curvature of 100 mm thick GFRP reinforced slab

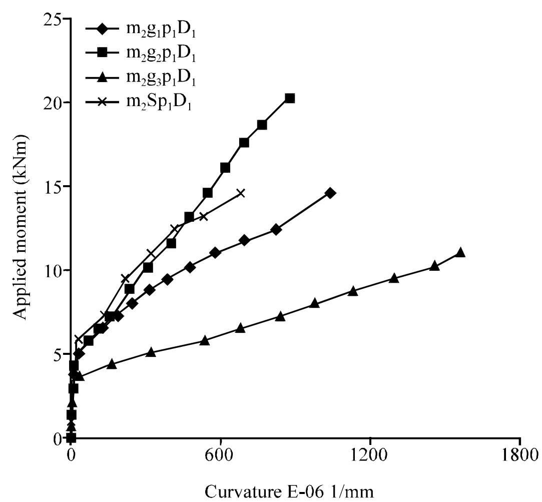

Fig. 7: Moment vs curvature for 100 mm thick slab reinforced with different types of reinforcements

(Vijayaprakash *et al*., 2004). This shows the higher stiffness of conventional steel reinforcements than GFRP reinforced slabs. Sand coated GFRP reinforced slabs experienced 30-40, 80-90 and 35-40% higher ultimate bearing capacities and 0.9, 0.66 and 1.25 times the deflections when compared to that of the identical slabs reinforced with the grooved GFRP, plain GFRP and Fe415 reinforcements, respectively. As the longitudinal reinforcement ratio of slabs increases from 0.82 to 1.15%, the ultimate load carrying capacities of GFRP reinforcements from 20-30% and the deflections and crack widths were not that much significant. Similarly an increase in the grade of concrete from 20 to 30 N mm^{-2}

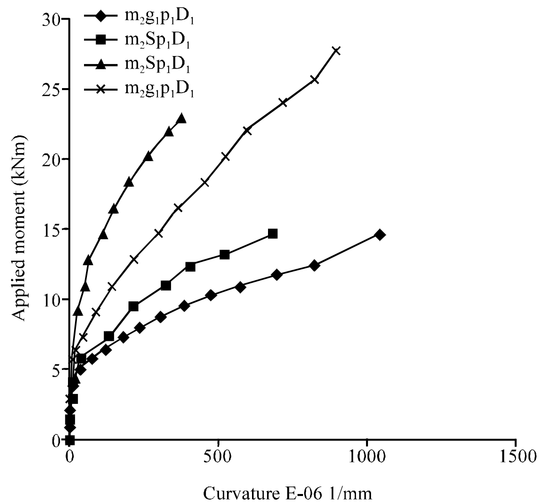

Fig. 8: Comparison of load and deflection values of 100 and 120 mm thick GFRP 1 and Fe 415 reinforced slabs

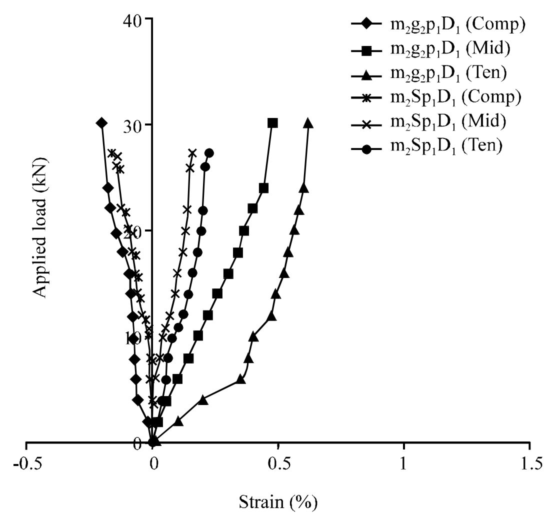

Fig. 9: Strains at different levels while loading statically for 100 mm thick grooved GFRP and Fe415 reinforced slabs

for the slabs results in 15 to 20% increase of ultimate load bearing capacities with insignificant reduction in deflection. By increasing the depth of the slab from 100 to 120 mm, the ultimate static load was increased by 82% and the deflection was reduced by 0.8 times. The strains at different levels while loading statically for 100 mm thick slabs are shown in Fig. 9. The experimental and theoretical results were in good accordance in the service conditions and in the ultimate conditions, some acceptable percentage of deviations exist as shown in Fig. 10.

Test Results under Repeated Loading

GFRP2 slabs experienced higher fatigue strength than the identical slabs reinforced with the GFRP1, GFRP3 and Fe415 reinforcements when subjected to same stress range with the same

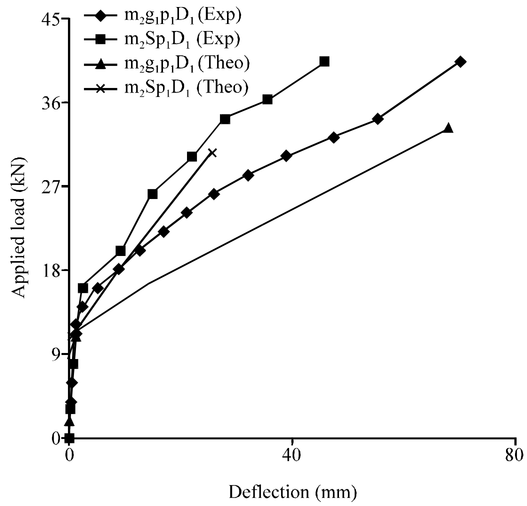

Fig. 10: Comparison of experimental and theoretical load and deflection values of 100 mm thick GFRP1 and Fe 415 reinforced slabs

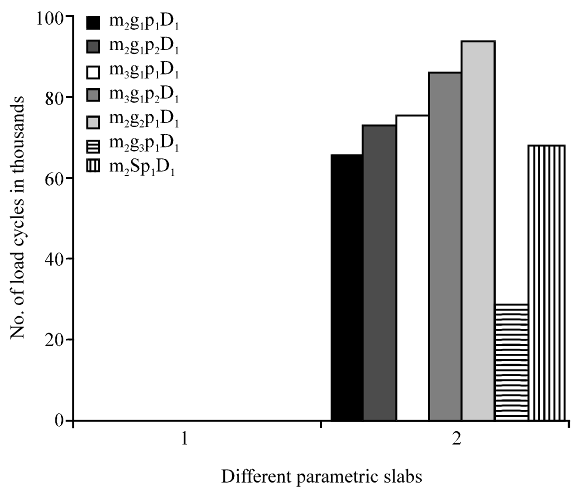

Fig. 11: Comparison of 100 mm thick slabs having different parameters when subjected to repeated loading

frequency. GFRP2 slabs experienced 1.4 times greater fatigue life than that of conventional slabs. The fatigue performance of GFRP1 reinforced slabs was similar to that of conventional slabs and GFRP3 reinforced slabs showed half of the fatigue performance of conventional slabs. By increasing the reinforcement ratio of slabs, the fatigue performance of $m_2g_1p_2D_1$ was increased by 1.3 times that of $m_2g_1p_1D_1$. On increasing the grade of concrete, the fatigue performance of $m_3g_1pD_2$ was increased by 1.2 times that of $m_2g_1p_1D_1$. The fatigue capacity of $m_2g_1p_1D_2$ was raised to 5.3 times the fatigue capacity of $m_2g_1p_1D_1$. During the repeated loading steps many strain gauges fixed to the reinforcements malfunctioned and the strain data could not be collected. Repeated application of the loads resulted in the higher deterioration of the slabs than static application of the loads. Figure 11 shows the comparison of 100 mm thick slabs having different parameters when subjected to repeated loading with the help of bar chart.

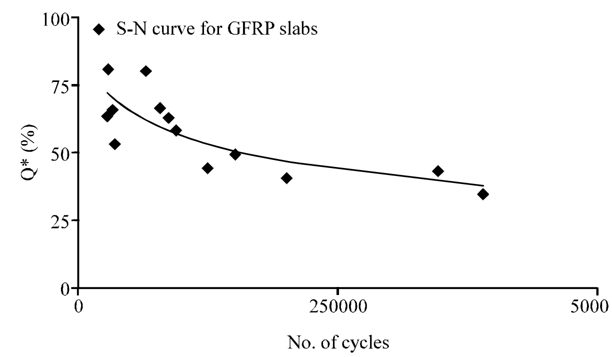

Fig. 12: S-N Curve-A regression analysis

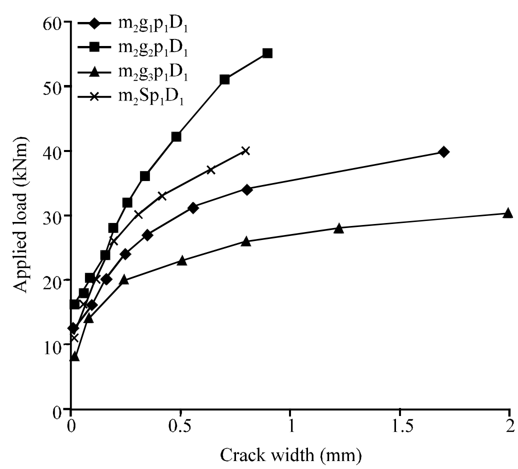

Fig. 13: Effect of moment (static loading) on crack width for 100 mm thick slabs

S-N curves are drawn from the test results for repeated loadings and are shown in Fig. 12. The equation regarding the relation between the operational stresses applied and the number of cycles is shown as follows:

$$Y = B^* \text{ LnN} + A \tag{1}$$

where, A and B are experimental constants derived from the test values, Y operational stress applied, N is the fatigue life of slabs in terms of number of load cycles. From the above study, the relationship between fatigue strength (which is the percentage ratio of maximum repeated fatigue loading and static ultimate loading and fatigue life) are shown in Fig. 12. Equation 2 is obtained from the regression analysis.

$$S = -12.868 \text{ Ln}(N_f) + 203.41 \quad \text{where } (R^2 = 0.6215) \tag{2}$$

Crack Growths and Modes of Failure

For all the GFRP reinforced slabs, first crack was initiated at midspan and was followed by a sudden increase in deflection due to stiffness reduction of the slabs. As the application of the load

Fig. 14: Rupture of GFRP reinforcement

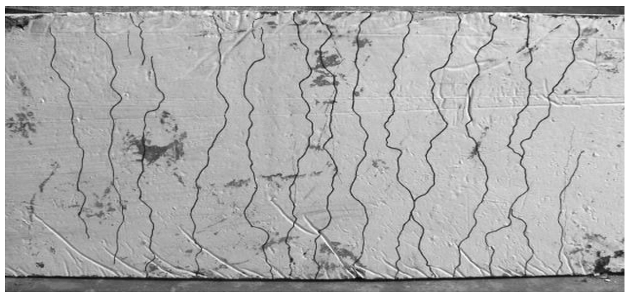

Fig. 15: Crack pattern of grooved GFRP reinforced slab

Fig. 16: Crack pattern of conventional slab

increased, enormous cracks were started to form and develop within the constant moment zone along the width of the slabs. The developed cracks were slowly enlarged and generated throughout the width of the slabs until failure occurred by the concrete crushing. In case of steel slabs, the first crack was initiated at midspan, but it was followed by lesser number of cracks, smaller crack widths and shorter deflections due to the greater stiffness of the steel reinforcement. Effect of moment (static loading) on crack widths for 100 mm thick slabs is shown in Fig. 13. The photographs showing the failure of the slabs are shown in Fig. 14-18.

From the experiments, it was observed that the slabs reinforced with GFRP2 reinforcements showed beneficial results in all the aspects than the slabs reinforced with the other reinforcements. The theoretical calculations of first crack load, first crack deflections, ultimate moments, ultimate

Fig. 17: Crack pattern of sand coated GFRP reinforced slab

Fig. 18: Crack pattern of plain GFRP reinforced slab

loads, ultimate deflections and crack widths displayed good accordance with the experimental results possessing acceptable percentage of deviations.

CONCLUSIONS

From the experimental results of forty numbers of slabs the following conclusions are summarized:

- The behaviour of slabs reinforced with GFRP reinforcements was linearly up to first cracking and after first cracking, with reduced stiffness under static loading condition. Due to the low modulus of elasticity and different bond characteristics of the GFRP reinforcements, slabs reinforced with GFRP reinforcements exhibited larger deflections and strains than those reinforced with conventional reinforcements.
- With the increase in thickness, grade of concrete, reinforcement ratio of the slabs, the static ultimate load carrying capacity of slabs were increased and the corresponding deflections, strains and crack widths were reduced.
- Deterioration of concrete slabs subjected to fatigue loads can be observed through the cumulative damage to the slab observed from the increase in the deflections and crack widths.

- GFRP reinforced concrete slabs had a better performance and longer fatigue life when compared to those reinforced with steel because of the equal values of the modulus of elasticity for GFRP reinforcements and concrete in addition to the linear-elastic behaviour of GFRP reinforcements. Sand coated GFRP reinforced slabs showed best fatigue performance than the other GFRP reinforced slabs. This might be due to the good bond strength of sand coated GFRP reinforcements with the concrete.
- GFRP2 reinforced slabs showed 30-40, 80-90 and 35-40% greater ultimate bearing capacities and 0.9, 0.66 and 1.25 times the deflections when compared to that of the identical slabs reinforced with the GFRP1, GFRP3 and Fe415 reinforcements, respectively.
- GFRP2 slabs experienced 1.4 times greater fatigue life than that of conventional slabs. The fatigue performances of GFRP1 reinforced slabs were similar to conventional slabs and GFRP3 reinforced slabs showed 0.5 times lesser fatigue life than conventional slabs.

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